Combining cameras and citizen science to define the distribution and behaviour of dingoes and foxes in New South Wales

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ABSTRACT

We used two survey methods - citizen science for private land and cameras for protected areas - to map the distribution of dingoes/wild dogs and foxes in NSW. Dingo/wild dog records were mostly confined to the east coast and ranges, with scattered locations in western NSW. This contrasts to the distribution of foxes, in which occupancy was high across most of the state. Data from 200 WildCount camera sites within protected areas also showed marked differences in the distribution of the two canid species. At the scale of the state, dingoes/wild dogs are uncommon, with the greatest concentration being in the north-east of the state, as well as a marked presence in the south-east. Foxes are common and widespread within protected areas, but less common in the north-east of the state. The camera data also indicated that feral cats are widespread within protected areas. The second aim of our study was to examine the WildCount data for behavioural patterns of the canid species. Foxes and dingoes/wild dogs significantly separated within two sub-formations of dry sclerophyll forest based on the Keith (2004) classification of NSW vegetation. From species pairwise interactions at sites, we found only limited evidence for significant interactions, and then only for the co-occurrence of fox-rabbit and fox-swamp wallaby, but no avoidance for any of the predators with each other. Camera records of the time of day of being active showed little effect of the presence of dingoes/wild dogs on the times of activity of foxes, but foxes curtailed the activity times of dingoes/wild dogs. From the analysis of inter-animal times at sites where both canids were recorded, there was little difference between the time since the other species was present. Thus, there was no evidence that dingoes/wild dogs or foxes inhibit the other from being at a site. We concluded that at the landscape level, both vegetation type and land tenure play a role in the interactions between dingoes/wild dogs and foxes. We also concluded that citizen science and cameras are complementary, not alternative techniques, especially as they sample different land tenures, and that cameras in protected areas and occupancy from citizen science have produced higher resolution maps and behaviour patterns than have been previously available. We can confirm that foxes are a ubiquitous threat throughout NSW, whereas dingoes/wild dogs are concentrated into a much smaller area of eastern, particularly north-eastern, NSW.

Key words wild canids, Keith vegetation formations, occupancy modelling, WildCount, protected areas, behaviour, community-based records, invasive species, cats, rabbits, swamp wallabies, spotted-tailed quolls, domestic dogs, community-based surveys, koalas, meso-predator release, scalp returns.

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Introduction

When the name matters: wild dog or dingo?

The primary aim of this study was to determine the distribution of dingoes/wild dogs in New South Wales, but first we consider the terms dingo, then wild dog. As Dixon (2019, pp 8, 45, 147) records, the Dharuk language (Sydney region) has given English such well-known words as boomerang (*bumariñ* = hunting/fighting boomerang), dingo (*din.gu* = domesticated dingo) and koala (*kula/kulawañ*). On the other hand, the scientific name of the dingo is neither well-known nor agreed upon. Its scientific name has changed over time and remains contentious, with some advocating *Canis dingo*, while others *C. familiaris* (Jackson *et al.* 2021; Smith *et al.* 2019). We do not enter that debate here, just note that it exists because the name is irrelevant to the way we conducted our study. One of our major objectives was to use data we had collected in a citizen science survey where the term "dingo/wild dog" was used to prevent confusion, and to maximise the response by not asking respondents to have to choose between dingo or wild dog. Hence the use in this paper of the term dingo/wild dog as we used it

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in the state-wide, community survey. Our second major objective was to utilise camera data from protected areas in the NPWS WildCount program, which uses terms to avoid distinguishing between dingo and wild dog in camera records. We present a photo in Appendix 1 of a dingo/wild dog as shown on the cover of the leading book on camera trapping by Meek *et al.* (2014).

Looking back over the two decades since A symposium on the dingo

In their concluding chapter on *A symposium on the dingo*, Dickman and Lunney (2001a) observed that "from the scientific (genetic) analysis presented by Wilton, the dingo is a species threatened by hybridisation – a threatening process long recognised as affecting dingoes (see Corbett)." Corbett (2001) stated that, "Hybridisation with domestic dogs remains the greatest threat to the continued existence of pure dingo populations." Wilton (2001) stated: "The effective conservation of the dingo in Australia requires that a purebred animal can be reliably distinguished from a hybrid domestic dog. Even though the dingo and the dog are closely related, differences in DNA between them can be used as the basis of a test to detect hybrids". In addition, pure dingoes are variable in colour (Crowther *et al*. 2014, Smith *et al*. 2019), most "wild dogs" in NSW have substantial dingo ancestry (Cairns 2021), and many dingo-dog hybrids are impossible to distinguish from pure dingoes morphologically (Parr *et al*. 2016). Given these considerations, we had made a common-sense choice in opting not to try to distinguish between dingo and wild dog in our 2006 state-wide citizen science survey, as had the decision-making process for camera trapping identifications in WildCount.

In their foreword to *A symposium on the dingo*, Dickman and Lunney (2001b) identified that the intent of the symposium "was to discuss whether the dingo qualifies as a threatened species under the NSW *Threatened Species Conservation Act 1995* and, more importantly, if it does qualify on biological grounds, what practical issues does it raise in wild dog control." They added, "As we go to press, the Scientific Committee is yet to make its decision. It is listening to public submissions and weighing new scientific evidence from genetics laboratories, field researchers and managers." The matter was not resolved, and the dingo has remained unprotected and the legislation is explicit on the point. Under the current Act, the NSW *Biodiversity Conservation Act 2016*, under the heading "Schedule 5 Protected animals", the Act states: "Any of the following that are native to Australia or that periodically or occasionally migrate to Australia (including their eggs and young)… mammals of any species (including aquatic or amphibious mammals but not including dingoes)."

Listing of Key Threatening Processes was provided for by Part 2 of the *Threatened Species Conservation Act 1995*. "As with two other introduced carnivores, the Cat and Red Fox, predation pressure on native fauna by Feral Dogs threatens a number of species, including the following threatened fauna:…" In 2009, the Scientific Committee made a "Final Determination to list Predation and Hybridisation by Feral Dogs (*Canis lupus familiaris*) as a 'key threatening process' in Schedule 3 of the Act" as, in the opinion of the Scientific Committee: (a) it adversely affects threatened species, populations or ecological communities, or (b) could cause species, populations or ecological communities that are not threatened to become threatened" (Major 2009). These decisions remain in the current Act, the NSW *Biodiversity Conservation Act 2016*, under "Schedule 4 Key threatening processes".

The most recent determination was made in 2020 as the papers from the 2019 dingo forum were being edited. In a lengthy review, the NSW Threatened Species Scientific Committee, established by the *Biodiversity Conservation Act 2016* (the Act), made a Final Determination to reject a proposal to list "The cascading effects of the loss or removal of dingoes from New South Wales landscapes" as a Key Threatening Process under Schedule 4 of the Act. The concluding opinion of the Threatened Species Scientific Committee was that: "(a) Despite there being correlative evidence that the loss of dingoes could adversely affect some threatened species or ecological communities, there remains a considerable difference of scientific opinion about the complexity of interactions involved, (b) 'loss or removal of dingoes' is ambiguous and ill-defined in relation to the extent, time-frame and area such 'loss or removal' is required to influence the functional role of dingoes, (c) Dingo predation adversely affects some threatened species." (Kerle 2020).

We note that while these academic and official government debates continue, high profile public anxiety and concerns about wild dogs and dingoes feature in the media. On one hand, there is a plea that, "the dingo should be included in the list of native animals threatened with extinction". This statement was in a letter by Susan Cruttenden to the editor of the *Sydney Morning Herald* on 23 July 2020 under the major heading, "Dingoes are native animals under threat, not feral pests." On the other hand, as exemplified in the same month in Local News 06 July 2020, under the heading "More than 300 wild dogs have been removed in the Upper Hunter" (Radio Hunter Valley Pty. Limited 98 power FM 2020), the item reads: "Hunter Local Land Service's (HLLS) Professional Wild Dog Controller Program launched just under three years ago in response to increasing dog attacks being reported in the Upper Hunter, particularly impacting outlying sheep properties which was affecting confidence in the local industry….The program is supported by Hunter Local Land Services, the Hunter Valley Combined Wild Dog Association, Australia Wool Innovation and local land managers including Glencore, Bengalla, Yancoal, MACH Energy, Forestry NSW, National Parks and Wildlife Service and FeralScan." "President of the Hunter Valley Combined Wild Dog Association, Frank Bragg said taking these killer dogs out of the system is helping to restore hope in the

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future of the sheep industry for local producers…. You can watch our video on the Professional Wild Dog Controller Program by visiting our Youtube channel: https://www.youtube.com/watch?v=ZsLcEYS75t8".

These views echo the concluding statement by Helen Cathles (2001) at the previous dingo symposium: "I'd like to reiterate two very important points from the landholders' perspective: 1) dingo and the wild dog attacks affect the entire farm enterprise and their community, it is not just limited to the sheep killed; and 2) we do need adequately funded pro-active management, accompanied with tolerance and understanding from all sectors".

The continuing clash of values was predictable from the opening statement by Alan Newsome (2001), the then pre-eminent dingo biologist, in his paper in the symposium on the dingo: "Dingoes and sheep do not mix; The presence or absence of dingoes basically determines whether cattle or sheep are run throughout Australia; Dingoes, however, help control vertebrate pest species (kangaroos, emus, rabbits, foxes and feral pigs)… and... There are no simple answers, and sometimes no easy compromises between the two imperatives to eradicate and to conserve." To examine that statement quantitatively, we compared the records of sheep numbers with the presence of dingoes/wild dogs in our citizen science survey. Given the high-profile debates and the polarised views, seeking clarity on such basic matters as their distribution becomes ever more pressing. Hence our detailed focus on defining the distribution dingoes/wild dogs in NSW.

Fundamental to both the academic debate, and the disparate public viewpoints, is the continuing need to know more about dingoes, their interactions with other species, and the significance of land tenure, particularly whether national park or private property, especially agricultural land. It is in that context that we address a basic attribute of populations, namely distribution (Lunney 1986). In the course of determining the distribution, opportunities arose to capture more information, such as asking additional questions on a survey form, or looking at time of day for activity patterns, as well as location, in a camera study.

Given our primary aim of determining the distribution of dingoes/wild dogs in New South Wales, the methods we selected reflect our approach to understanding of the ecology and behaviour of these contentious canids. The methods we employed also gathered information on other relevant species (Lunney *et al.* 2009), and we have included them in this study because of their importance to understanding the distribution of dingoes. The most important is the European red fox *Vulpes vulpes*. It is a recognised threat to native fauna across Australia (Woinarski *et al.* 2014) and foxes became listed as a key threatening process under NSW legislation in 1998 (DPIE 2020). Questions regularly arise about the interactions between these two canid species. Our methods can contribute to that enquiry. Other species of relevance to the distribution of dingoes are feral cats *Felis catus*, another alien invasive predatory species and a threat to native wildlife (Woinarski *et al.* 2014, 2019). Feral cats became listed as a key threatening process under NSW legislation in 2000 (DPIE 2020). The parallel question is: how and where do they co-exist with the canids? One of our methods (cameras) can shed some light on these questions.

Methods

A novel approach: combining cameras and citizen science to define the distribution

We employed two complementary methods to determine the distribution and relative occupancy of important species from a management and conservation perspective. Our first method was to extract information from a major, state-wide community-based, now called citizen science, survey in 2006, where we used detectability and occupancy statistics to interpret citizen science data.

The standard procedure in a community wildlife survey is to ask whether respondents have seen a particular, easily-identified species. We have published the results for the koala *Phascolarctos cinereus* (Lunney *et al.* 2009, 2010), and we here turn our attention to the dingo/wild dog, which was another of the 10 iconic or readily-recognisable species in our 2006 survey. We have now added a level of certainty to our maps, as a varpsi value, along with the level of occupancy of the species. The psi and varpsi values are explained in detail later in the methods and become visually clear in the relevant figures in the results. It is an important addition to the concept of occupancy.

The fox was another species in the survey. Wildlife managers and conservation biologists recognise that the fox is now ubiquitous, which is why we deliberately included it (OEH 2011; Woinarski *et al.* 2015). A reply by a respondent with a fox marked on the map provided a location for a survey, and if another species, such as a dingo/wild dog, was not marked for that location, then we have accumulated evidence of the absence of that other species at that location. This allowed us to calculate occupancy (Lunney *et al.* 2009), with our recent addition of a corresponding level of accuracy. The dingo/wild dog and the fox are the two relevant species we report here from our 2006 citizen science survey. However, to overcome a limitation of citizen science surveys, a low return rate from protected areas, i.e. national parks and nature reserves, a separate method was needed. WildCount offered that prospect.

In 2012, the NSW National Parks and Wildlife Service (NPWS) instituted a camera-based survey, called 'WildCount', to monitor wildlife throughout eastern NSW with camera trapping restricted to the national park estate (NPWS 2020). Camera-trapping has recently come

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into its own and, in 2012, the first international camera trapping colloquium in wildlife management and research was held at Taronga Zoo, Sydney (Fleming and Banks 2014; Meek and Fleming 2014). WildCount features an array of 200 camera sites in the eastern, forested part of NSW, and its contribution has been noted in an examination of the value of national parks for conserving fauna (Lunney *et al.* 2017). Dingoes/wild dogs, foxes, cats, and prey (swamp wallabies *Wallabia bicolor* and rabbits *Oryctolagus cuniculus*) are readily identified on camera, as are spotted-tailed quolls *Dasyurus maculatus*, which is a nationally endangered species on mainland Australia. We cover this rare native carnivore in a separate study, but we note that the fox is recognised as a major threat to quolls. Cats and dingoes are also considered to be threats to quolls (Woinarski *et al.* 2015). Camera traps have a distinct advantage of recording both the date and the exact time that an individual of a recognisable species triggers the camera. For example, Robley *et al.* (2014) were able to assess the power to detect change in fox occupancy, and Bengsen (2014) reported his analysis of camera trap surveys to detect effects of population management. WildCount gave us the opportunity to look at how the various species of interest not only partitioned space, but also time, thereby providing behavioural insights into how potentially hostile species can co-exist.

At the outset of our studies, most maps of the distribution of dingoes and foxes showed the general area of the distribution of the dingo and associated species in just one colour, the most popular example being the maps in the immensely valuable *Mammals of Australia* (van Dyck and Strahan 2008) with the new edition by Baker and Gynther (in prep.) retaining this format. For some enquires, these maps are sufficient, but for research and management purposes they are inadequate because they do not distinguish between areas of high or low occupancy. For more detailed location records of species regarded as agricultural pests, FeralScan (2020), including WildDogScan, FoxScan and FeralCatScan, is a useful resource, showing location data, for example on wild dogs. It is a citizen science project of the NSW Department of Primary Industries and the Centre for Invasive Species Solutions. For even more detailed investigations, such as looking for interactions among species, or their relative distribution, or where efforts are needed to manage species in various locations, more searching methods are needed. The extra detail is more demanding of resources, so the questions being asked need to be sharper. WildCount and our citizen science survey provided the extra level of detail required.

The questions that we were able to address from both the citizen science survey and WildCount were:

1. For dingoes/wild dogs and foxes, what is the level of occupancy across NSW and the degree of accuracy of the levels of occupancy in each location?
2. Within the protected areas in eastern NSW, where are dingoes/wild dogs, foxes, and cats located, and what behavioural attributes can be detected, such as does the time of day of movement change when they co-occur, what is the time interval between the appearance as a camera image of one species and the appearance of the next species?
3. What is the value of cameras in detecting the presence of a species and can the cumulative total of records at a site over time, in years, provide information concerning the sustained deployment of monitoring wildlife with cameras?
4. Is there an association, or habitat difference that is other than random, between foxes and dingo/wild dogs using pairwise comparisons of species including the prey, rabbits and swamp wallabies?

A changing pattern of land use, and occupation by native species and invasive species as pests

Besides further refining the current distribution of dingoes/wild dogs and foxes in NSW, we should also see the dingo distribution in historical context, as well as through the eyes of other observers, such as land managers in agricultural landscapes. We do not plan to undertake a history of change, but simply to note that a century ago the landscape was different as noted by other scholars (Glen and Short 2000) and, in today's agricultural enterprises, there is a specialist focus that adds a key dimension to the picture of the distribution and management of these important canids (DPI 2020).

Citizen science survey

For all of NSW, although primarily for private land, and thus most of the State, we drew on our 2006 citizen-science, community wildlife survey. On side A of the survey form was a questionnaire, on side B was an A2 sized colour map depicting towns, roads, rivers, National Parks and State Forests. For eastern and central NSW, the maps were at a scale of 1:500 000, and for western NSW 1:850 000. At this scale, most maps allowed a resolution of 1 km for the sightings marked by respondents. Sides A and B of the form are shown in Lunney *et al.* (2010). We posted 213,685 survey forms to rural areas of NSW. The allocation procedure produced a threshold level of 473 surveys delivered per postcode, i.e. all postcodes containing up to 473 delivery points were used. In total, we selected 278 postcode areas in NSW. This selected more areas of low density of human population in the west of the state to ensure all areas were represented. We excluded metropolitan areas in the ACT, Sydney (except for the Campbelltown area), Newcastle and Wollongong. To enhance the return rate, we used Reply Paid Mail. The details of the 2006 survey are covered in Lunney *et al.* (2009, 2010), but here we have provided new analyses of occupancy,

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along with certainty. The 2006 survey was designed to obtain spatially explicit data on the presence or absence of 10 recognisable species across the state of NSW and the Australian Capital Territory. The questionnaire requested information on the following species: koala *Phascolarctos cinereus*, spotted-tailed quoll *Dasyurus maculatus*, platypus *Ornithorhynchus anatinus*, echidna *Tachyglossus aculeatus*, brushtail possum *Trichosurus* spp., wombat *Vombatus ursinus*, dingo/wild dog, fox, deer (any species) and cane toad *Rhinella marinus*. Each species was analysed, with the results for dingo/wild dog and fox reported here. We used a design modified from MacKenzie *et al*. (2006), which depends on several repeat observations at a site, rather than the approach employed by Dillman (2007), which requires a high response rate if the researcher is to assess the knowledge, or the trends in attitude, in a community.

The set of models used to estimate the probability of a dingo/wild dog being detected took into account the location of the other nine species in the survey. The resulting map shows ψ (psi), the likelihood of a dingo/wild dog being present in a 20 × 20 km grid square within NSW, calculated using the number of survey returns reporting dingoes/wild dogs in relation to other wildlife species. The colour coding of ψ (yellow to purple, not present to definitely present) and colour intensity of σ^2_ψ (faint for high variance, dark for low variability indicating certainty) enable a geographical display across NSW of dingo/wild dog and fox occupancy and our confidence in the estimated values. The basic model uses the method of maximum likelihood to estimate dingo/wild dog and fox presence (ψ), the variance of this estimate (σ^2_ψ) and the probability of detecting (p) at least one dingo/wild dog or fox given they are present in the area. These are calculated for each grid square using the following grid square variables

s ~ number of active sub-grid squares (16 sub-grids of 5 × 5 km), where active refers to respondents reporting sightings of any species

k ~ the total number of respondents reporting any species within the grid square

A ~ the total number of times sub-grid squares were identified as having a dingo/wild dog, across all sub-grids and all respondents;

D ~ the total number of sub-grids with at least 1 dingo/wild dog sighting.

The ψ value estimates the proportion of each grid square that has dingoes/wild dogs and together with the p value will tell us the chance of a similar survey (using local observations) detecting dingoes/wild dogs in the grid squares. The σ^2_ψ value shows us how much the data supports the estimated values. Low values close to zero show strong support for the estimates while higher values up to 1.0 indicate a paucity of support for the actual estimate. A ψ value of 1.0 arises where dingoes/wild dogs were reported in all active sub-grid squares. Values close to zero reflect a large number of wildlife sightings but few or no dingoes/wild dog sightings. Higher values reflect increasing support by the data for dingo/wild dog presence throughout the grid square. If no wildlife of any species was detected in a 20 × 20 km grid square, that grid was deemed to be not surveyed and is left blank on the map (see Lunney *et al.* 2009 for more details). The process was repeated for foxes.

As presented in Lunney *et al.* (2009, 2010), we received 16,694 replies to the 2006 community (citizen science) wildlife survey, a return rate of 7.7%, which greatly exceeds the usual return rate of less than 2% for commercial surveys and promotions (Australia Post, contact officer for 'reply paid post', May 2006). The response rate was similar between males and females. Of the 7,486 respondents who provided answers to the male/female question, 52% were males and 48% were females. As a point of comparison, the adult (over 20 years old) population of NSW is 51% male, 49% female. The returned forms yielded 48,841 animal sightings distributed widely across NSW. Of these records, there were 2,902 dingo/wild dog and 13,263 fox records and when lodged in 2007 in the NSW wildlife atlas, i.e. BioNet, they represented 27.8% and 58.9% of all records (respectively for each of the taxa in the NSW wildlife atlas (as of 25 August 2020, using all records, the figures had dropped to 19.9% and 20.8% respectively).

The conclusions we drew from these studies were that the combination of public survey, which is map-based, with the estimation of site occupancy, has wide application where conservation actions on private land, and community participation, will be integral to the success of proposed planning decisions or wildlife-management programs. The practical application of this technique enhances the capacity of spatially explicit public surveys to provide a rigorous and repeatable basis for ecological studies. One application is presented in this paper as we proceed to define the distribution of both dingoes/wild dogs and foxes in NSW.

How we assembled and used survey data

Roadkill

Respondents were asked to add an additional mark to their map records of a species if it was dead on road. Roadkill is a persistent threat for many species and identifying locations can assist in managing roads and identifying the scale of the problem. We used spatial analyses (GIS) to locate the identified locations onto the different road types. We combined the five levels of roads that were available for spatial analyses to produce three levels: primary, arterial and local. The roadkill was expressed as a percent of the total records for the species, in this case, dingo/wild dog and fox.

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Data from the A side (the questionnaire side) of the state-wide citizen survey

a) Does this species occur in your area?

To the question: 'Does this species occur in your area?', we recorded the questionnaire results for both dingo/wild dog and fox from the questions on the A side of the survey, as shown in Lunney *et al.* (2010). We present the results in maps showing the boundaries of the NSW Local Land Services (LLS) regions to make the display both vivid and geographic as well as to juxtapose the LLS regions and the occupancy maps. These maps from the questionnaire are not intended to duplicate the occupancy map, although drawn from the same set of survey returns, rather the intent is to give a separate portrait of the density of the presence of these two canids to further emphasise the differences in their regional presences, but primarily to provide a visual comparison to the maps of 'increasing, staying the same or decreasing', and responses to the question of whether the species was a pest in their area, as well as comparisons to maps of scalp returns from dingoes from the late 19th century, as shown in by Glen and Short (2000), the maps of wild dog distribution produced by the Department of Primary Industry (DPI) and the dingo and dog maps produced by the Atlas of Living Australia (ALA 2020).

b) Dingoes/wild dogs: increasing, decreasing or staying the same?

To determine directional changes in the populations of dingoes/wild dogs and foxes, we mapped community perceptions from the state-wide community wildlife survey. The layout of the questions, on the A side of the survey form, is shown in Lunney *et al.* (2010). To quantify directional trends (increasing, decreasing or staying the same) indicated by the survey data, we assigned a value of 1 to each "decreasing" survey response, 2 to each "staying the same" and 3 to each "increasing", and then calculated an average value for each local land services region. We present the data in a readily-recognised format of the NSW Local Land Services regions (LLS 2020).

c) "Is this species a pest in your area?"

This question in the state-wide, citizen science, survey on whether a species was considered to be a pest or not was presented as a yes or no option. Again, we display the results within the LLS boundaries, especially as they allow a ready comparison with the replies of presence and of population change. We also considered the relative pest status of dingo/wild dog and fox with the other eight species to see the extent of the differences by respondents across all species. (There was no "don't know" response option, so we have assumed that leaving a question blank either means "don't know" or that the question was locally irrelevant.)

d) Survey completion rates for the questionnaire in the state-wide, citizen science survey for each LLS region

The percentage of respondents who replied to each question is considered in relation to the percent replies for each of the three questions listed above as a, b, c. Regional variations in response rates can be read as indicative of the differences in status of these two canids across NSW, and that has considerable management implications, as well as a reflection of public attitudes. For example, where the species is not a pest, a low level of response can be expected to the question, and the converse applies, where it is a pest, the response rate will predictably be high.

A changing pattern of land use, and occupation by native species and invasive species as pests

We drew on a) a study by Glen and Short (2000) for maps of scalp returns from dingoes a century past and b) a survey by NSW Primary Industries (DPI) of land managers of the locations of wild dogs in NSW in 2016.

Sheep and wild dogs don't mix

To explore one of the factors influencing perceived pest status, we analysed the interaction between the density of sheep, using the data presented in Allen and West (2013), and positive returns from the state-wide citizen survey for dingo "pest" and dingo "observed", and fox "pest" and fox "observed". Each observation was assigned to a sheep density category (sheep/km^2) following Allen and West (2013). We undertook spatial analyses to examine whether dingoes/wild dogs, and foxes, mix with sheep, or if there is an inverse relationship. Each citizen science survey return was assigned to an IBRA bioregion (Version 7 of Thackway and Cresswell 1995), and a sheep density in sheep/km^2 (from Allen and West 2013). As the geographic locator was postcode, and postcodes can straddle multiple geographic and administrative boundaries, the dominant bioregion was assigned to each post code. Dominance was assigned by the greatest number of properties from each post code contained in each bioregion or LLS region.

Domestic dogs

Under NSW law, dogs and cats must be registered by the time they are 6 months old. Registration requires the dog or cat to be microchipped. This is managed by the NSW Office of Local Government. Registered domestic dogs are such a common feature of Australian life that their relative numbers and distribution warrant comparison with dingoes/wild dogs to capture how the two categories – domestic and wild – are distinguished across the NSW landscape. We examined the distribution of domestic dogs in NSW by postcode in the year 2013. A summary of the numbers can be found on the official NSW website (OLG 2020). The website also provides the number of reported dog attacks on people and animals.

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WildCount in protected areas

a) Distribution of species

For the protected areas of NSW, i.e. the national parks and nature reserves, we drew on the National Parks and Wildlife Service (a division within the NSW Department of Planning, Industry and the Environment DPIE) "WildCount" array of 200 camera sites in 146 national parks and nature reserves for the first six years (2012-17) of data collection and analyses. Site selection was based on stratified random sampling to ensure unbiased sampling. At each site there were four cameras in a square, set ca 500 m apart. The cameras were set off track, with a generalised bait of oats, honey and peanut butter. Each site was set for 14 days, and although some sites ran for longer, we limited our analyses to 14 days to allow comparisons among the sites. In some sites, in some years, not every camera worked every day, so we used a period of 10 days or more. The cameras were set in autumn over a period covering three months, i.e. not all sites were set simultaneously. The images were examined and identified where possible, and a spreadsheet of sightings per camera, per site, per day with time of day (hh:mm:ss)was created. The first six years yielded 1,160,000 images of all species, which were resolved into 126,000 sequences, i.e. records where images are terminated by a 20 second gap or a different species. We identified 20 seconds as the time gap where the frequency count of inter image times radically changed from numerous to relatively few. We allowed for different species sequences to overlap (provided the 20 second rule still held) where a subsequent identified species would normally terminate a sequence.

Swamp Wallaby dominated the data, with 509,000 images and 41,000 sequences. For the primary species of interest in this study, the fox had 38,000 images and 3,487 sequences, cat 4,348 images and 530 sequences, dingo 2,722 images and 269 sequences and quoll 2,371 images and 254 sequences. We note that foxes had 14 times more sequences than dingoes, and cats almost twice as many as dingoes. This is the dataset we used, after carefully checking the input spreadsheet for errors. The basic WildCount data of sites with species have been entered into the publicly-accessible BioNet system run by DPIE.

b) Habitat preferences based on selection of Keith vegetation formations

An analysis of the habitat preferences was undertaken by classifying each of the 200 WildCount sites according to Keith (2004) vegetation formations using GIS layers. The analyses used numbers of sequences captured at each site of the study species to examine their habitat preferences. The analyses compared the pattern of camera sites (which were uniformly random across the WildCount study area) for each vegetation formation against the pattern of sites where the species were detected.

Selection as being significant was determined by Chi-squared analysis.

c) Pairwise comparisons

Using the procedure of binomial proportions, we examined pairs of species occurring at a camera site. The question is whether species segregate, or not, across the landscape, with each occupying different locations. The more specific questions are whether dingoes/wild dogs and foxes avoid each other spatially, or whether cats avoid either dingoes/wild dogs or foxes. Conversely, species could be seeking other species, such as predator to prey. In that context, we examined both swamp wallabies and rabbits and the predators – dog, fox, cat. We considered the occupancy of a site over a number of years, recognising that a species could be at a camera site, but not present in the 14-day photographic period in any one year. We define a species domain as all sites where the species is recorded over 5 years, i.e. we used plus or minus two years as the number of years based on the life expectancy of these species in the wild – their life expectancy in captivity being much longer. Basically, the reason for the number of years examined was constrained by data availability, which serendipitously reasonably corresponds to the animal lifetimes in the wild (Biosecurity Queensland 2020; The fox website 2020). The tables give plausible limits of the number of sites with both species, given that the first species is detected independently of the detection of the second species. This table was used to rate the actual number of sites that detected both dingoes/wild dogs and foxes, then dingoes/wild dogs and cats.

d) Behaviour - time of day of movement

We used the camera data to examine behaviour, in this case the time of day of movement. The questions are: what are the times of day that the dingo/wild dogs, and foxes move, does the presence of either canid influence the time of day of movement of the other? We examined the data for significant correlations. The potential influence of one species on another, when co-occurring, is reflected by the between-species correlation using the 24 hour-of-day relative frequencies of species activity captured by camera.

e) Inter animal times

We examined the number of WildCount sites where both dingoes/wild dogs and foxes were detected. We looked to see if one species would directly follow another, or leave a wide gap in timing before moving along the path of another species. We repeated that procedure for dingoes/wild dogs and cats. The tables give the length of time between species. The 'no reset' means the analyses were not reset if species other than the two in question passed the camera in between the pairs of species of interest. We used all sequences for all six years (2012-2017).

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Results

Occupancy maps from citizen science survey

The dingo/wild dog state-wide distribution shows a marked concentration in the eastern division of NSW, with the highest level of certainty in the north-east strip of NSW, continuing down the coast and through south-east NSW, but with a high level of variance, i.e. lower certainty, in the south-east part of the State (Figure 1). The few notable cells of high level of certainty in the central and western divisions of the State show that the dingo/wild dog exists in NSW from the eastern seaboard to the arid zone, but almost all the area recorded as occupied is along the coast and ranges. The colour yellow on extensive areas of NSW shows no presence of dingoes/wild dogs, with the deep yellow indicating a high level of certainty. The gaps around Sydney and Canberra reflect the fact that the survey went to rural and regional NSW and the ACT, but not the large metropolitan centres. The blank areas are locations without data, which are mostly in the western part of NSW where there are far fewer people to respond to a survey. Hence, dingoes/wild dogs are almost entirely confined to the eastern part of NSW, i.e. the coast and ranges, but also do occur in the arid inland.

In contrast, the distribution of foxes is extensive, covering the eastern two thirds of the State, and reaching well into the arid zone (Figure 2). The very few locations coloured yellow, indicating an absence of foxes, is in stark contrast to the deep purple and blue colours, which indicate that the fox occupies all habitats in NSW at a high level of certainty. Again, the blank areas are locations without data, which are mostly in the western part of NSW where there are fewer people to respond to a survey.

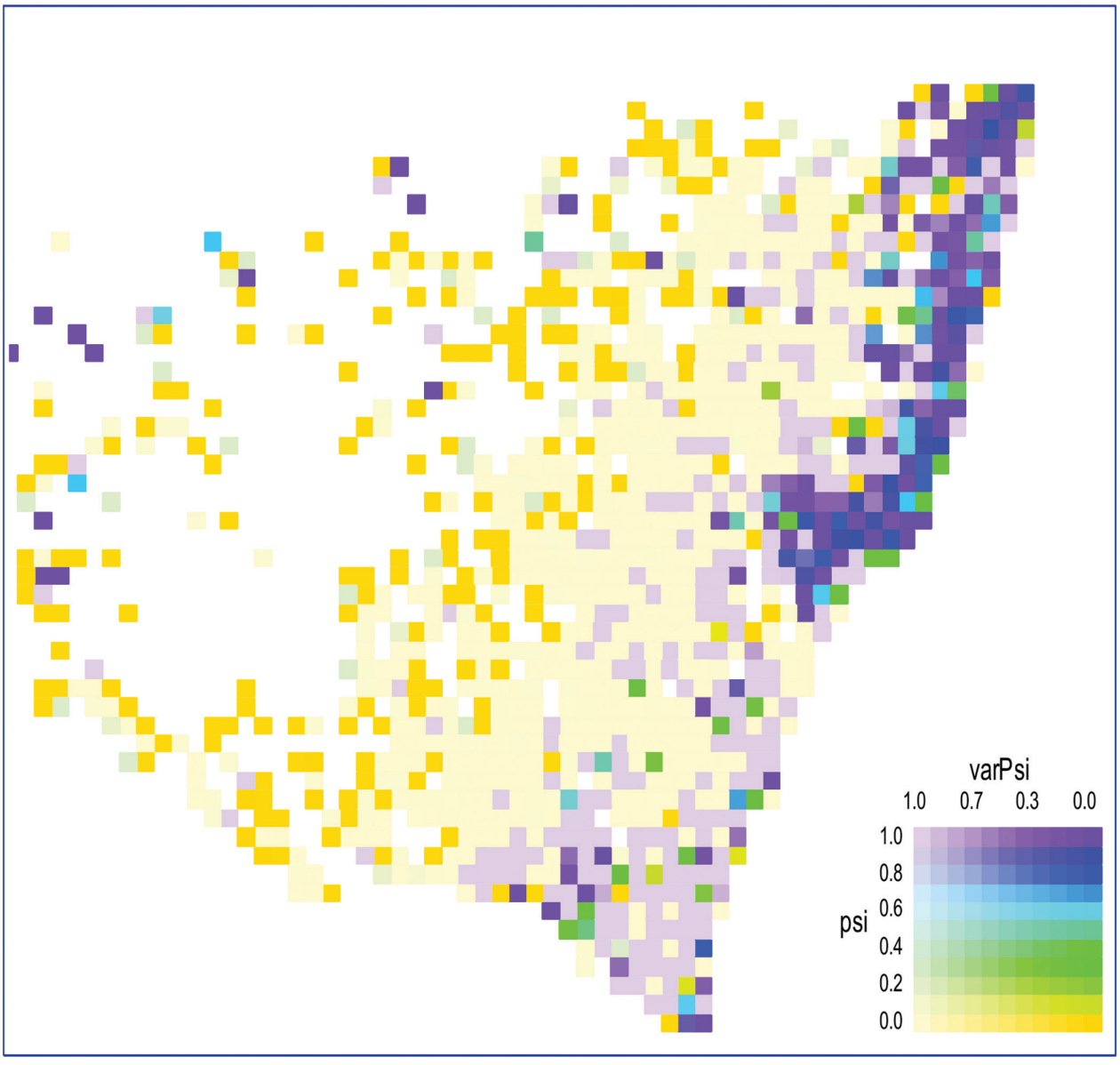

Figure 1. The occupancy, presented as ψ (psi), and certainty/reliability of occupancy (varPsi) for dingoes/wild dogs in NSW, derived from a state-wide community survey in 2006.

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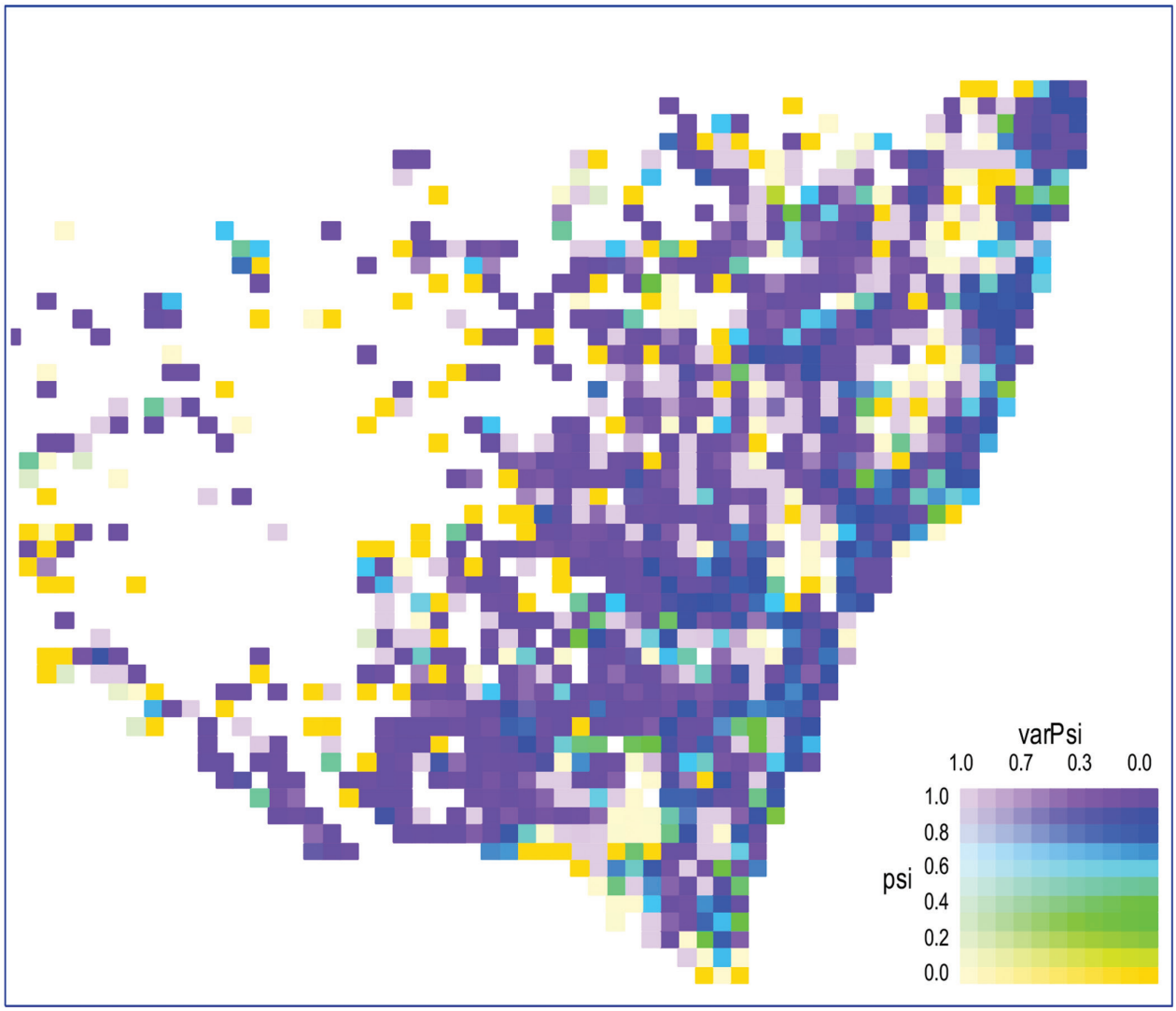

Figure 2. The occupancy, presented as ψ (psi), and certainty/reliability of occupancy (varPsi) for foxes in NSW, derived from a state-wide community survey in 2006. The gaps in the east of the state, especially the north-east, correspond with the location of national parks and nature reserves (see Figure 3).

For the dingo/wild dog in the northern part of the state, there is a sudden drop in occupancy after the coastal strip. That marked drop off coincides with the national parks and State Forests on and near the Great Dividing Range, where fewer people live and thus few citizen science surveys were possible (Figure 3). The distribution of dingoes/wild dogs in national parks is covered in detail in the next section on WildCount data. Noticeably, dingo/wild dog occupancy remains low across the state to the western border. This leaves a marked distribution along the north coast of NSW at a high level of certainty.

The distribution of the fox shows a reduction in occupancy in the north-east of NSW after the coastal strip and before a sustained high level of available data across the state. That dip in occupancy corresponds with the location of national parks and nature reserves, and State Forests on and near the Great Dividing Range, where citizen science replies are weakest because people do not live there (Figure 3). It also corresponds to the north-south band where dingo/wild dog occupancy fades. In contrast to the dingo/wild dog, the high level of available data reflects that the predominant land use is in private hands. It is the conspicuous low level of occupancy for both dingoes/wild dogs and foxes in National Parks and Nature Reserves that makes working with the WildCount data so valuable. From an examination of the maps of both species together, there is no indication of that either the dingoes/wild dogs or foxes occur at other than high density on private land in north-east NSW. This provides an important point of comparison with their presence in protected areas as revealed by camera results (see next section).

Data from the A side, the questionnaire side, of the state-wide citizen survey

a) "Does this species occur in your area?"

The results for dingo/wild dog and fox, presented in Figures 4a,b, show a striking difference between the two canids. For dingoes/wild dogs, the two highest regions

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are north coast and Hunter, followed by the northern tablelands, with the lowest being the central west region. In contrast, in every region, the fox has a much higher level of observations than the dingo/wild dog. As expected, the greater Sydney region has the lowest level in our study because the survey did not go the metropolitan regions. In contrast to the dingo/wild dog, the lowest level of fox observation is the north coast and Hunter regions, but still their level of observations is much higher than the dingo/wild dog.

b) Dingoes/wild dogs and foxes: increasing, decreasing or staying the same?

The dominant opinion was 'staying the same' in seven regions for dingo/wild dog, but increasing in four regions (Murray, Riverina, North West and Northern Tablelands). Foxes were recorded as increasing through all the LLS regions in the central part of the state (Murray, Riverina, Central West and North West, Central Tablelands and Northern Tablelands) (Figures 5a,b). Notably, no region recorded a perceived decrease for either species.

c) "Is this species a pest in your area?"

For the fox, there was a high level of response that it is a pest, with the highest reading being in the Riverina, Central West and Northern Tablelands. Leaving aside the unsurveyed Greater Sydney Region, the North Coast and Hunter regions showed the lowest level of pest status, although still definitely a pest (Figure 6b). Dingo/wild dog revealed a mixed level of responses across the LLS regions, with the highest pest status reading being on the Northern Tablelands (Figure 6a). The Central West and North West were the lowest on this pest scale, but considered to be a pest nonetheless.

A graphic display is presented of the relationship between the observations (expressed as a percent of the respondents in each bioregion in NSW) and the percent of the respondents who selected "yes" to the yes or no question of whether the animal is a pest in their area (Figure 7). The standout feature is that foxes were considered to be a pest by almost everyone, followed by dingo/wild dog. Irrespective of the percent of respondents who made the observation, the majority considered the

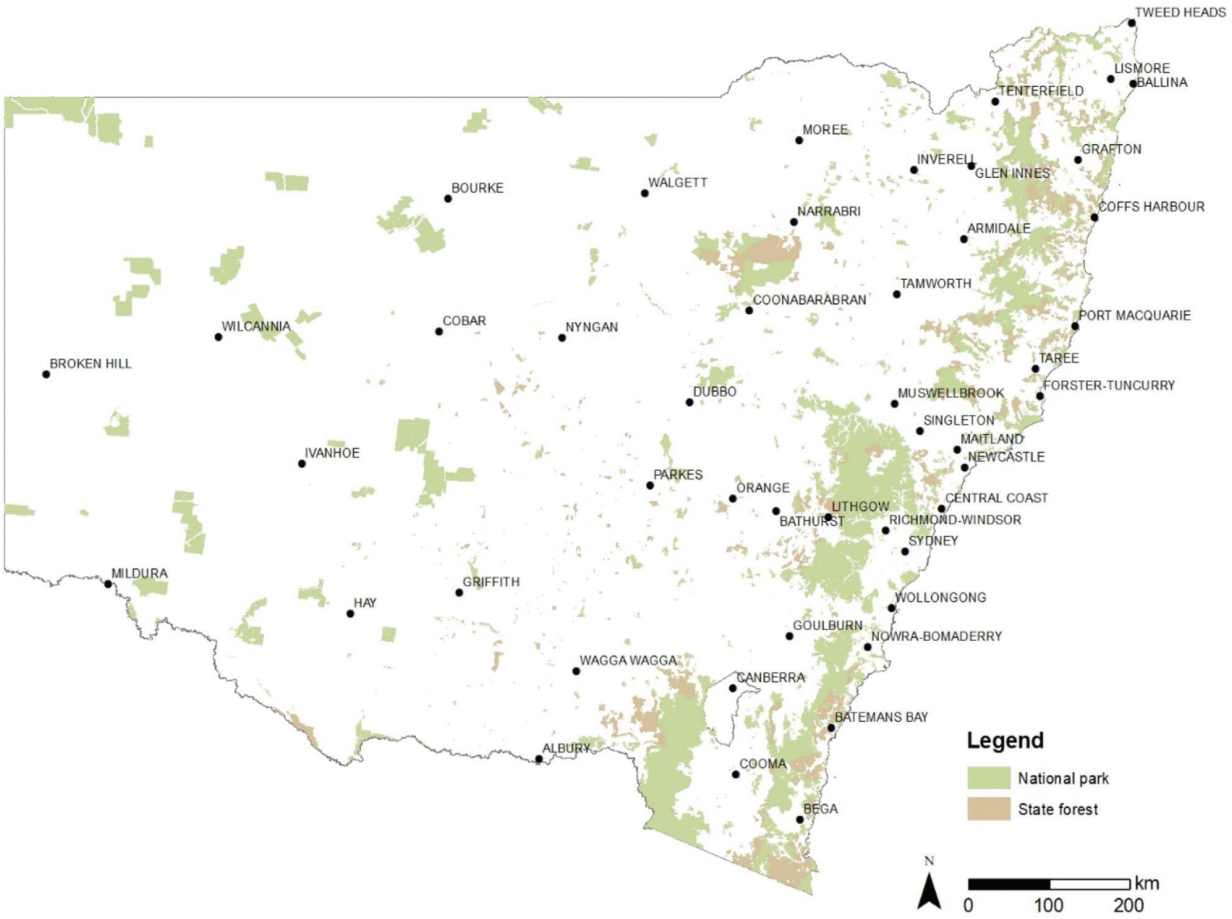

Figure 3. The location of National Parks and Nature Reserves, as well as State Forests, in NSW. This map provides a basis for comparison with the citizen science occupancy maps for dingoes/wild dogs in Figure 1, and foxes in Figure 2. Occupancy maps for these Crown lands from citizen science surveys can be expected to be much lower than citizen science surveys on private land where there are far more people. This map also shows the spatial extent of the National Parks and Nature Reserves. The WildCount sites in Figures 10, 11 and 12 are confined to the eastern third of the state.

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fox to be a pest species. By contrast, species such as the platypus, were exceptionally low on the pest scale (and for native species the response rate was very low, thereby identifying the ability of the respondents to distinguish differences among the species).

d) Survey completion rates for the questionnaire in the state-wide, citizen science survey for each LLS region

The percentage of respondents who replied to each question was considered in relation to the percent replies for each of the three questions listed above, as a, b, c (Table 1). Regional variations in response rates can be taken as indicative of the differences in status of these two canids across NSW. Compare the Central West and the Northern Tablelands regions where there were similar rates of responding to the question of dingo/wild dog (74%) and fox (69%), but sharply different rates of response to the question of whether the dingo/wild dog was a pest - 11% for Central West compared with 33% for Northern Tablelands.

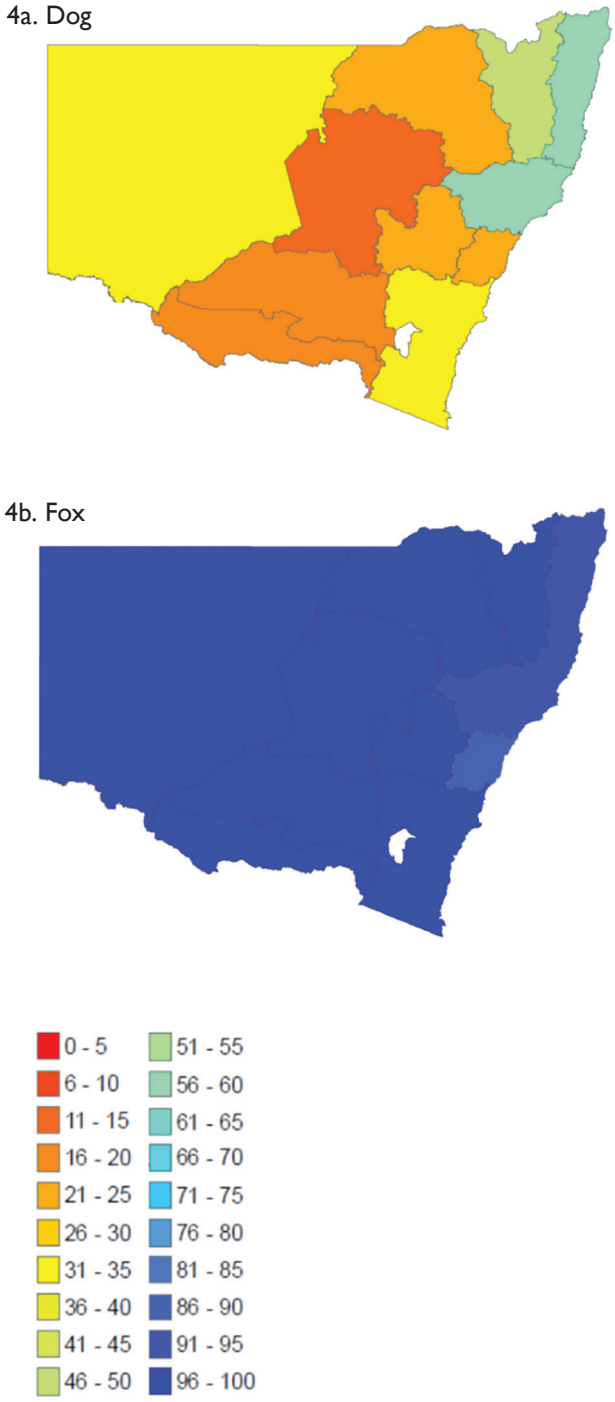

Figure 4. 4a. (dingo/wild dog), and 4b. (fox). Positive reponse rate, by local land services (LLS) region, to the question "does this species occur in your area?".

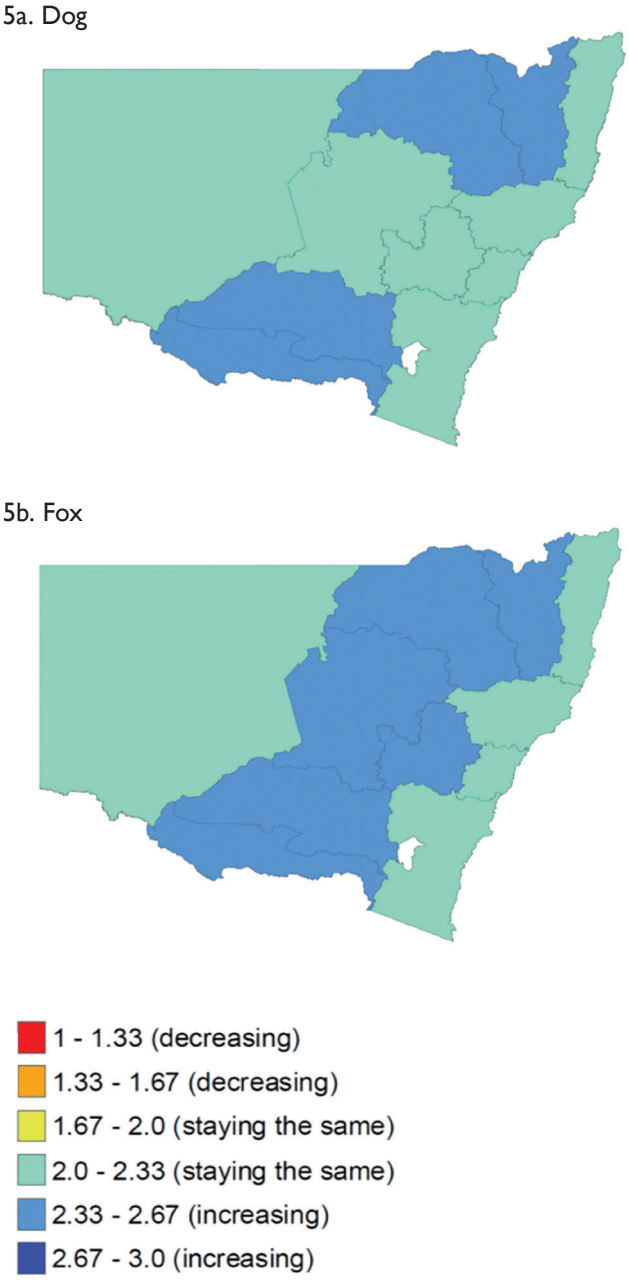
5a. Dog
5b. Fox
1 - 1.33 (decreasing)
1.33 - 1.67 (decreasing)
1.67 - 2.0 (staying the same)
2.0 - 2.33 (staying the same)
2.33 - 2.67 (increasing)
2.67 - 3.0 (increasing)

Figure 5. 5a. (dingo/wild dog) and 5b. (fox). Perception of population change for dingo/wild dog and fox depicted by local land services region. Results are based on the question: "is this species increasing, decreasing or staying the same in your area?". Where the numbers are close to 1 = decrease (Red), close to 2 = staying the same (yellow or aqua) and close to 3 = increasing (dark blue).

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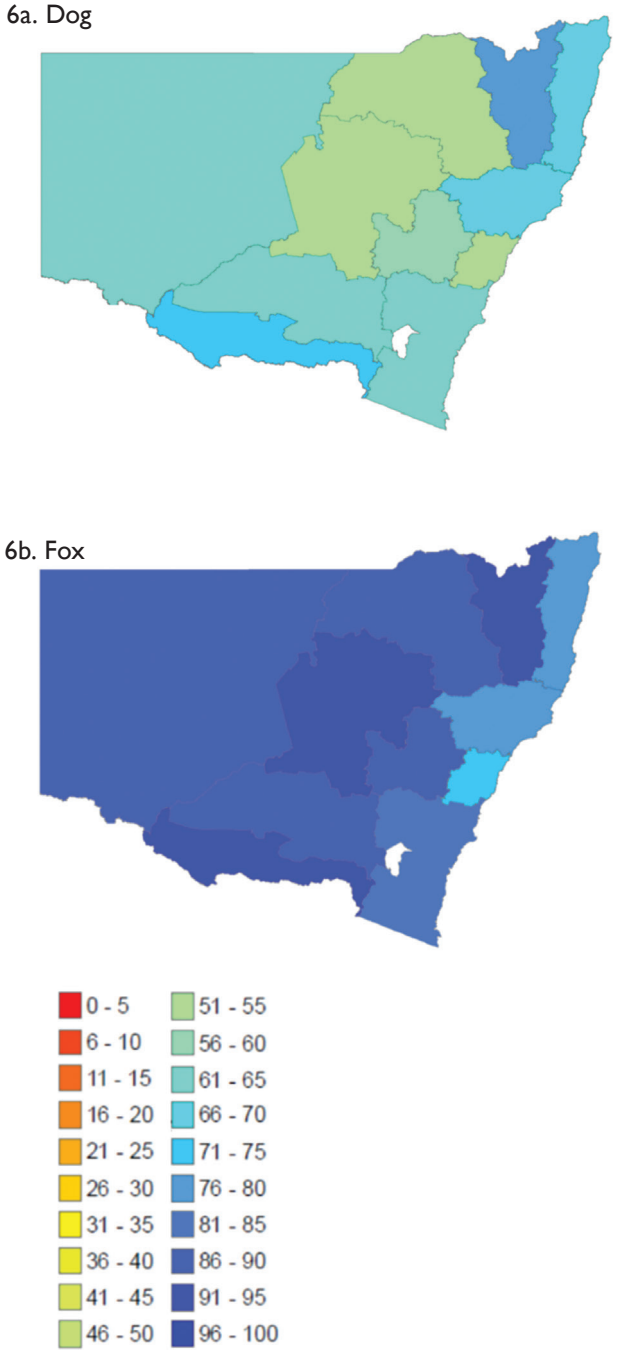

Figure 6. 6a (dingo/wild dog) and 6b (fox). The percentage of responses for each Local Land Services region that indicated yes to the question: "is this species a pest in your area?". Only responses that answered "yes" or "no" (rather than leaving it blank) are included in these percentages

Those differences come into much sharper focus when the maps of pest status show a low level for the Central West, but a high level for the Northern Tablelands. By implication, where the species is not a pest, there is a low level of response to the question, and the converse applies.

Sheep and wild dogs don't mix

Our analysis found that wild dogs have an inverse relationship to sheep stocking densities (Figure 8.) The higher the density of sheep, the lower the density of wild dogs. In contrast, there was no relationship of sheep and foxes. Fox density remained the same irrespective of sheep density.

Roadkill

The analyses of roadkill show a higher rate, all roads combined, for foxes, with 4.1% of total records being recorded as dead on road, compared to dingo/wild dog at 0.6% (Table 2). There was a distinct increase in percent records per road type, with primary roads standing out as recording the highest rates of roadkill, especially for foxes at 33.3% of records on primary roads, i.e. highways. By contrast, foxes on local roads showed only 1.8% roadkill.

Distribution of registered domestic dogs

From 1 January 2020 to 31 March 2020 (3rd Quarter 2019/20), there were 2,465,897 microchipped dogs in NSW (OLG 2020). The number of dog attack incidents reported by all councils for the quarter year was 1,121 on people, and 997 on animals (OLG 2020). A dog attack was defined to include any incident where a dog rushes at, attacks, bites, harasses or chases any person or animal (other than vermin), whether or not any injury is caused to the person or animal. Domestic dogs are present in all parts of the state reflecting the distribution of the human population - highest along the coast (particularly Sydney) and declining westwards (Figure 9).

A changing pattern of land use, and occupation by native species and invasive species as pests

The dingo scalp returns analysis mapped by Glen and Short (2000) for NSW shows a high level of contrast across the state, and through time (1886-1930) (Appendix 2). Of interest is the period 1896-1900. The regions of what are now the LLS regions of Central West, and the north and south of Central West, show a high level of scalp returns, as does western NSW, particularly the north-west of the state. In contrast, the north coast of NSW shows an exceptionally low rate of scalp records. By 1926-1930, the map has a pattern more akin to the present occupancy map (as shown in Figure 1), with the concentration of dingoes/wild dogs being in the north-east of NSW, on the coast.

The DPI 2016 map for survey returns from professionals in the field of land management presents yet another pattern of distribution (Appendix 3). The difference to the occupancy map in Figure 1, i.e. from the citizen science survey, is the strong presence of wild dogs in western NSW in the DPI map, particularly the north-west of NSW. The emphasis in this 2016 DPI map parallels the 19th century distribution from scalp returns. Among the important points to see is that the occupancy map, based on citizen science, gives only a modest clue that dingoes/wild dogs occur in the north-west of the state, reflecting a limitation of community surveys – if there are only a few people reporting over

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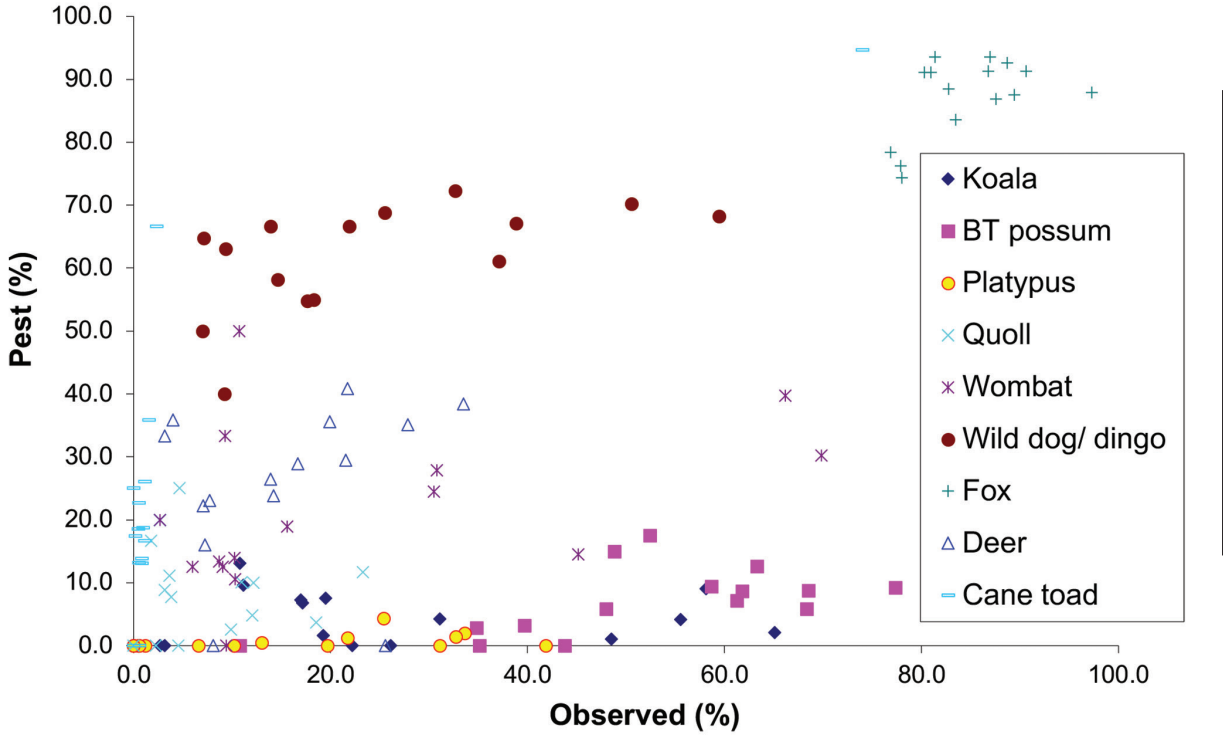

Figure 7. A graphic display of the relationship between the observations (expressed as a percent of the respondents in each bioregion in NSW) and the percent of the respondents who selected 'yes' to the yes-or-no question of whether the animal is a pest in their area. The standout feature is that foxes are considered to be a pest by almost everyone, followed by dingo/wild dog, and irrespective of the percent of people who made the observation, the majority considered it to be a pest species.

Table 1. Survey completion rates for the state-wide questionnaire (as a percentage) by LLS region. N= the number of replies from each LLS region; dog and fox observed is the percent of the respondents who answered that question; dog and fox change in numbers, either increasing, staying the same, or decreasing, shows the percent of respondents who answered that question; and again, for dog as a pest, fox as a pest, the percent is of the number of total replies for the LLS region, irrespective of whether the answer was yes or no to the question on the species being a pest.

	N	Dog Observed %	Fox Observed? %	Dog Change in numbers? %	Fox Change in numbers? %	Dog a pest? %	Fox a pest? %
Central Tablelands	691	76	89	16	73	21	77
Central West	379	74	84	8	77	11	80
Greater Sydney (ex Metro)	1156	68	86	16	62	20	68
Hunter	1847	74	81	35	62	41	68
Murray	314	72	88	11	75	15	80
North Coast	1933	72	84	35	61	40	68
North West	260	61	84	13	72	18	74
Northern Tablelands	270	69	82	29	73	33	76
Riverina	452	76	85	14	75	17	76
South East	2257	73	91	21	72	28	78
Western	247	80	91	25	79	27	81

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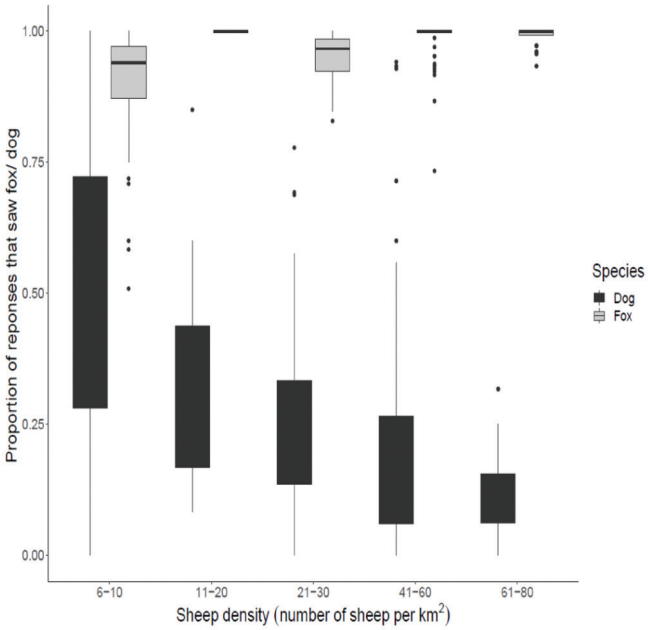

Figure 8. Boxplots of the reporting rate (as a proportion) of wild dogs and foxes from the state-wide citizen science survey for each sheep density class (from Allen and West 2013), replicated by postcode. There were no records from the 31-40 density class, so it was omitted from the graph.

Table 2. The map-based records of dingoes/wild dogs recorded as dead on road, with analyses to three levels of road type.

	Dog and fox records per road type. Number dead on road/total records (% dead on road)		
	Local	Arterial	Primary
Dog	3/1556 (0.2%)	5/451 (1.1%)	4/78 (5.1%)
Fox	112/6187 (1.8%)	148/979 (15.1%)	114/342 (33.3%)

a large area, then the result will be weak. Thus, we need the expert map as produced by DPI, it enlarges the pattern of distribution. We can also note that scalp returns, and the 2016 DPI map, are essentially drawing on the same type of professional local knowledge, even though they differ in time.

WildCount

a) Dingo/wild dog, fox and cat distribution in protected areas

For dingoes/wild dogs in national parks and nature reserves, the dominant feature is the relatively high concentration in the northern part of the State, and in the south-east, as shown by the larger stars (Figure 10). The size of the stars, showing average psi values, is directly related to the number of dingoes/wild dog sequences recorded across 6 years and 4 cameras at a site. The dots are locations of the camera sites. The dots (though some are obscured by stars) total 200. Noticeable is the fact that most of the 200 wild count sites did not record a dingo/wild dog over the six years 2012-2017. Unlike the occupancy map, there is not a noticeable east-west trend, but it is crucial to note that all sites are within protected areas, which is the measurement boundary of the WildCount study.

In contrast to dingoes/wild dogs, foxes were widespread, present at most WildCount sites, and with a high frequency over the six-year study period, as shown by the large orange triangles, with noticeable gaps only in the north-east (Figure 11). With the important exception of the north-east of NSW, there is no noticeable east-west trend in distribution within the national park estate. The north-east deserves special attention because it is evident that, within protected areas, dingoes/wild dogs dominate relative to foxes. This does not occur elsewhere, and this dominance is evident only within protected areas.

The distribution of the camera sites with cats can be characterised as widespread, and common (Figure 12).

b) Habitat preferences based on selection of Keith vegetation formations

The vegetation formation analysis revealed a significant difference in use between dingo/wild dog and fox. Using the WildCount data and vegetation formations, the chi square using frequencies for dingo/wild dog compared with fox reveal a significant difference in their selection of vegetation formations, although both species used all formations (Table 3). In dry sclerophyll forests, there was a reversal in the use of the two sub-formations, with dingoes/wild dogs selecting the shrubby sub-formation, and foxes preferentially selecting the shrub grass sub-formation. With rainforests, the dingoes/wild dogs markedly selected this formation compared with the fox. Within our limited data sets, we detected no significant difference between cat and dingo/wild dog, and cat and fox.

c) Pairwise comparisons

There was only limited evidence for significant pairwise interactions from this analysis. The results were: fox-rabbit was significant co-location in 2012, 2014, 2015, 2016, but not for 2013, 2017 (Table 4); for fox- swamp wallaby, significant co-location in 2012, 2013 2014, 2017, but not for 2015, 2016. No significant findings, either co-location or avoidance, for any years for fox-dog, fox-cat, dog-cat, dog-rabbit, dog- swamp wallaby, nor for cat-rabbit, cat-swamp wallaby pairwise interactions.

d) Behaviour - time of day of movement

We examined the combinations of time of day of movement of all species, but we have limited our reporting here to the dingo/wild dog and fox, where there was a significant

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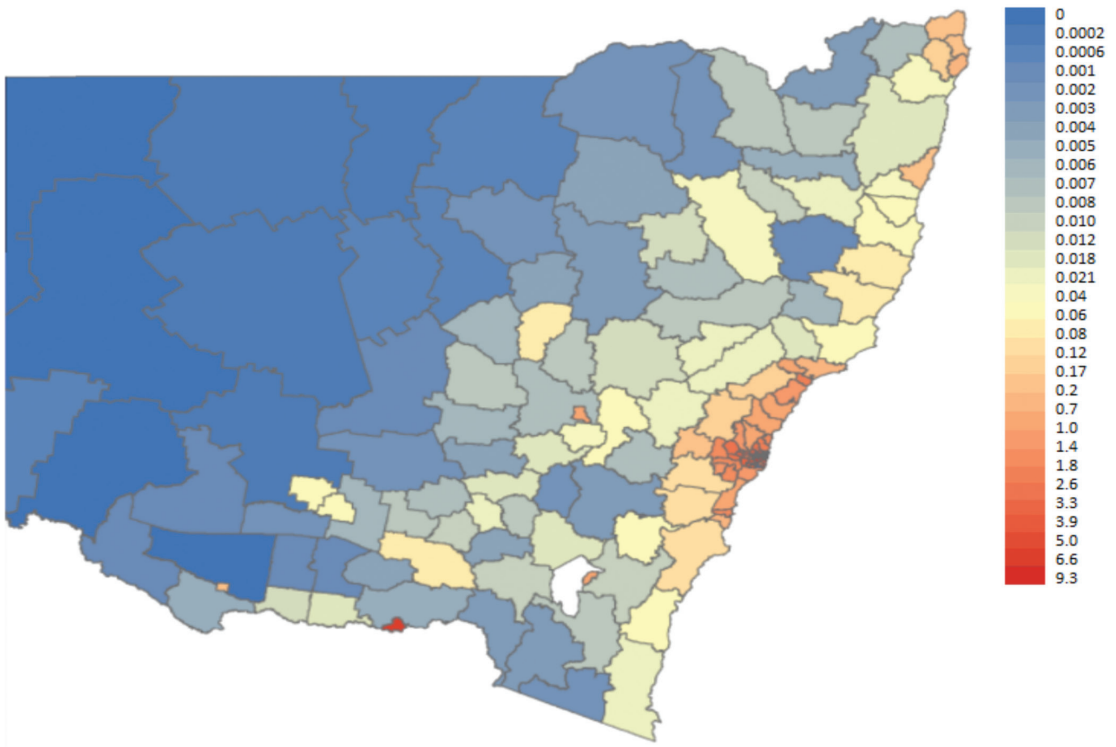

Figure 9 Density of registed dogs per postcode (dogs per ha). Data source: NSW Office of Local Government for 2013. Red shows highest density of dogs/ha, blue shows very few dogs/ha.

correlation. The times of movement of foxes show a minor shift (correlation 0.75) to more activity from dusk to midnight, though with approximately the same spread for the rest of the day in the presence of dingoes/wild dogs (Figure 13a,b), but dingoes/wild dogs show a marked shift (correlation 0.13) in time of day in the presence of foxes (Figure 14a,b). The centre of the graphs is midnight, and the dingoes/wild dogs now moved across the full span of the night, rather than a gap in activity around the middle of the night. Noticeable from the graphs is that foxes are predominantly nocturnal, in contrast, the dingoes/wild dogs eschew the midnight hours, but move throughout the full span of day and night in the presence of foxes.

e) Inter animal times

For the inter-animal times at sites where both dingoes/wild dogs and foxes were recorded, there was little difference between the time since the other species was present. There were 9 sightings of a dingo/wild dog following the presence of a fox within the period of 5 hours to 1 day, and 17 sightings within 2 days (Table 5). Conversely, there were 5 foxes within 5 hours of a dingo/wild dog being present, and 17 within 2 days. Given the low numbers, there is no basis for considering that either the dingo/wild dog or the fox inhibits the other from being at a site because the time from dingo to fox or fox to dingo were similar (Table 6).

The inter-animal times of dingo/wild dog to cat, then cat to dingo/wild dog co-occurring at the same sites (Tables 7 and 8) show only a small sample of both species, meaning that there was little species overlap in our WildCount dataset. In considering the possibility that a cat would avoid a location where a dingo/wild dog had been present, it seems from the limited amount of data available that 2 cats had appeared within 5 hours, and a total of 3 within a day, of dingo/wild dog being present, but dingo presence following a cat was slightly slower, none within 5 hours, yet 3 within a day. From the little evidence available, there is no indication of one species avoiding the other with respect to time, given the other species was identified at the site.

Discussion

The primary finding

This study has determined, at a high level of resolution, the distribution of dingoes/wild dogs in New South Wales, both within and beyond the protected areas of eastern NSW. Their distribution is largely confined to the east coast and ranges, with more certainty of records in the north-eastern part of NSW. There are scattered locations in the west of the State at a high level of certainty.

Comparison with other maps of dingo/wild dog distribution and with other species

FeralScan - WildDogScan

The pattern of distribution we report is consistent with the map in FeralScan (2020), called WildDogScan, including what FeralScan displays as very high numbers on the north coast and ranges based on landholder reports. (We note

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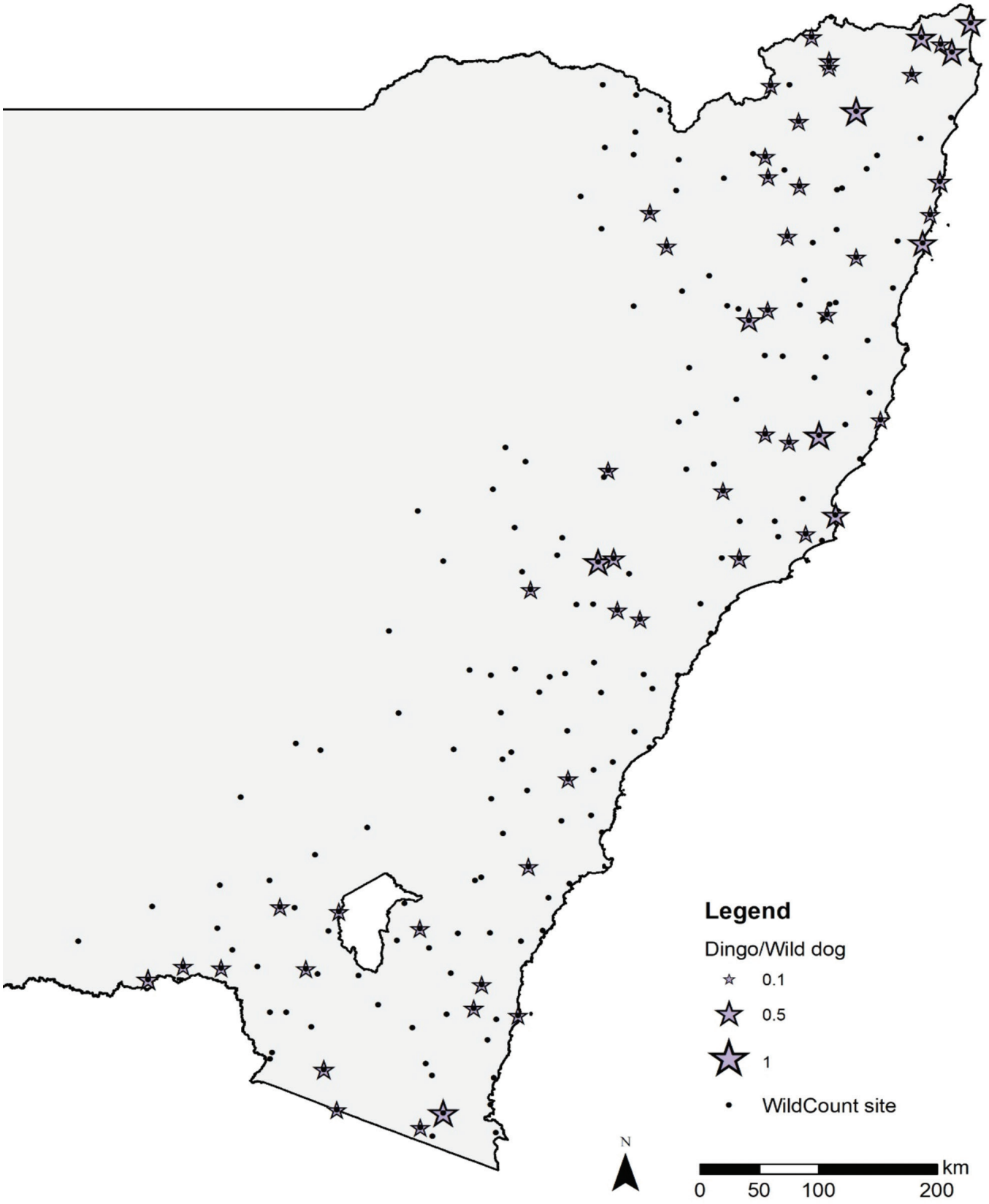

Figure 10. The distribution of dingoes/wild dogs in national parks over the six years (2012-17), presented as ψ values. There is a marked concentration in the northern part of the state. The dots are WildCount sites.

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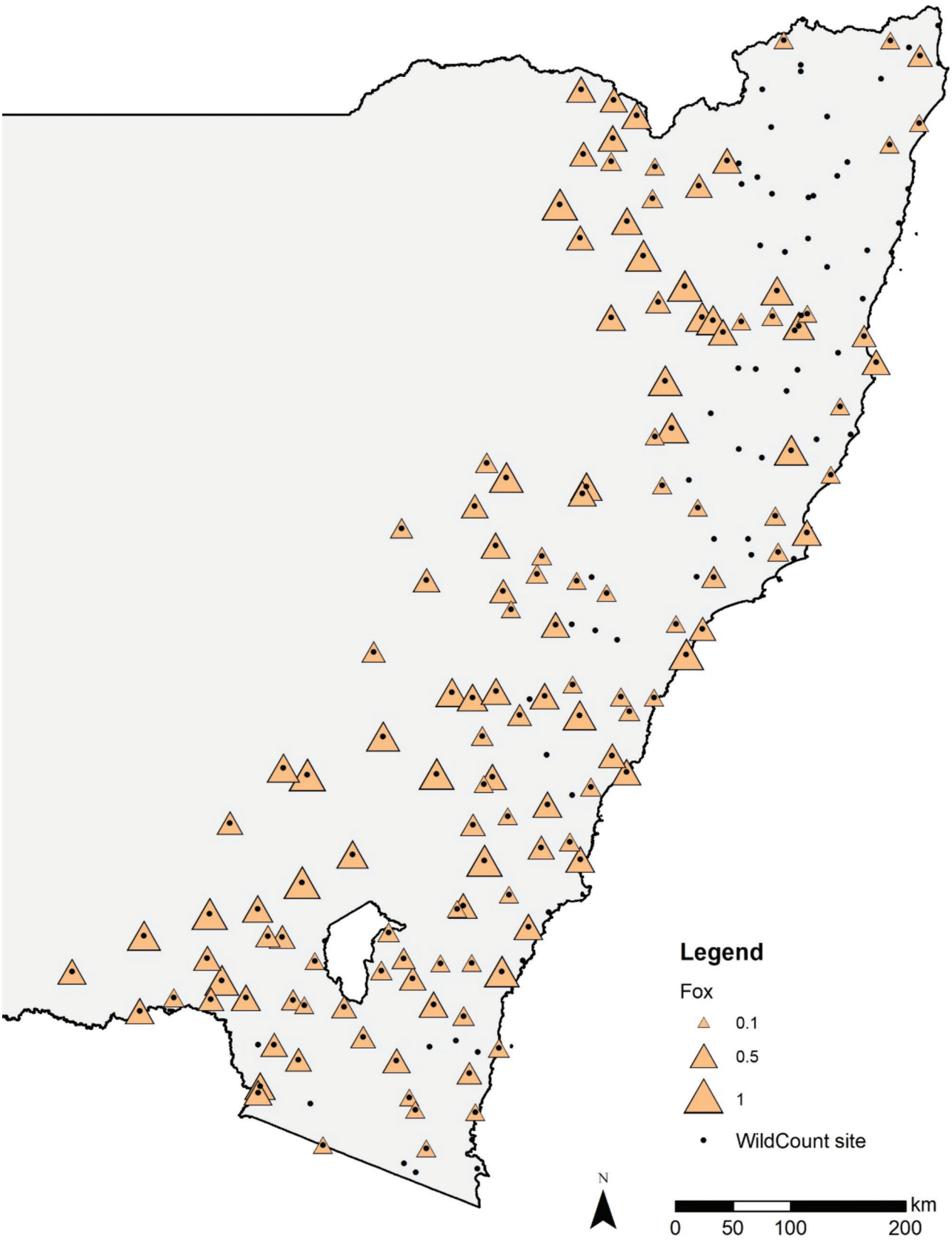

Figure 11. The distribution of foxes in national parks over the six years (2012-17), presented as ψ values. The only perceptible gap in the distribution is in the north-eastern part of the state. The dots are WildCount sites.

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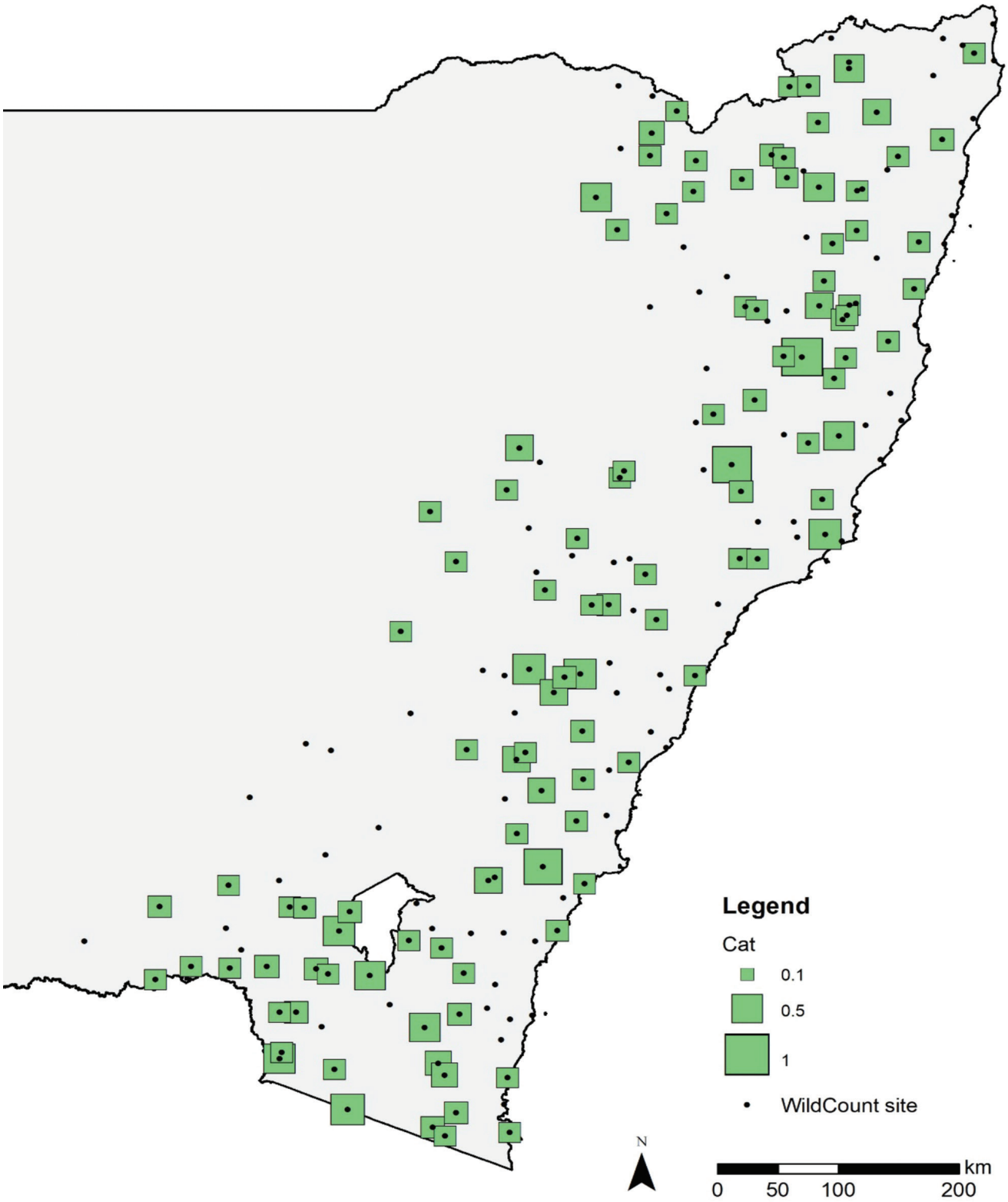

Figure 12. The distribution of cats in national parks over the six years (2012-17), presented as ψ values. The dots are WildCount sites.

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Table 3. WildCount chi-squared analysis using Keith vegetation formation frequencies for dingoes/wild dogs compared with the relative frequency of foxes. (χ^2= 32.3, df = 9, p <0.05)

Formation code	Formation	Relative frequency of foxes	Observed frequency of dingoes/wild dogs
6	Dry sclerophyll forest (shrub grass sub-formation)	133.7	78
7	Dry sclerophyll forest (shrubby sub-formation)	103.2	197
2	Wet sclerophyll forests (shrubby subformation)	48.6	19
3	Wet sclerophyll forests (grassy sub-formation)	48.6	41
1	Rainforests	42.5	13
8	Heathlands	24.3	20
4	Grassy woodlands	18.2	67
0	Cleared	18.2	17
10	Freshwater wetlands	18.2	4
11 12 9	Various	12.1	12

Table 4. Extract from species pairwise summary of site counts in 2012 giving overlaps and probabilities. Using standard occupancy data with up to 3 years either side of current year to establish home range.

WildCount Species		Site counts				Domain size			Domain overlap probability	
First	Second	First species	Second species	Overlap	Total (6 years)	First species	Second species	Overlap	that low or lower	that high or higher
Fox	Rabbit	72	22	16	139	135	53	49	99.65%	1.39%
Fox	Swamp wallaby	72	168	70	196	135	189	128	100%	0.00%

that WildDogScan presents the data as a point per record rather than an occupancy map.) What is noticeable, from the WildDogScan map, is the gap where the protected areas are located. FeralScan is headlined as "citizen surveillance - where you help map feral animals and the damage they cause. A landholder, community, industry, government & business collaboration." The FeralScan site invites the reader to "Help map feral animal sightings in your local area" and states that it was launched in 2009 - Now [July 2020] hosting over 260,000 community records." Thus, being a community-based approach, it has the strength of many sets of eyes seeing and recording, but it is remarkably limited within protected areas. This parallels the 2006 occupancy mapping in our study.

FeralScan does not aim to collect data from landholders to assess the distribution and numbers of animals across NSW, it encourages people to record wild dog activity where doing so might help with the management of wild dogs. It is only ever going to show some of the areas where these species occur.

In addition, we need to consider the 2016 DPI wild dog map, which shows a high level of occurrence of wild dogs in western NSW, especially the north-west of the State (Appendix 3). We note that wild dogs are found across NSW, "however, the eastern ranges, the coastal hinterland and tablelands have the highest populations" (DPI undated) in the *NSW Wild Dog Management Strategy 2017–2021* (DPI 2017). The wild dog distribution map for NSW was assessed and compiled in 2016 by DPI based on information provided by major land management organisations including NSW LLS and NPWS (Peter West DPI pers. comm. October 2020. This map used formal datasets (where available) and perception-based information from land managers based on their knowledge using standard definitions for relative abundance classes. Given those methods, it could be argued that the interpretation of the definitions for high, medium and low density may have differed across NSW especially, as the DPI state, the eastern part has the highest populations. In short, the west may have high populations by local reckoning, but lower than the east. Further, since perceptions were part of the method, the high density in the west could reflect perceived impact of wild dogs rather than just density, as the map indicates. Among the lessons that could be drawn is that the aim of a map, and the methods used, need to be stated and understood if the map is to be properly interpreted. Thus, we can make a more general statement that maps of distribution cannot be viewed as just a simple, objective picture of where a species occurs, does not occur, and at what density.

In contrast to the 2016 DPI wild dog map, our occupancy map relied entirely on community records, and people are scarce in western NSW, so our map lacks information about the presence of dingoes/wild dogs in many locations, e.g. no data, or very little data. However, WildDogScan does record a high density of wild dogs in the western regions of NSW. This contrast reflects a difference in the objectives and methods of our occupancy map, the 2016 DPI wild dog map, and WildDogScan, i.e. three maps, three different

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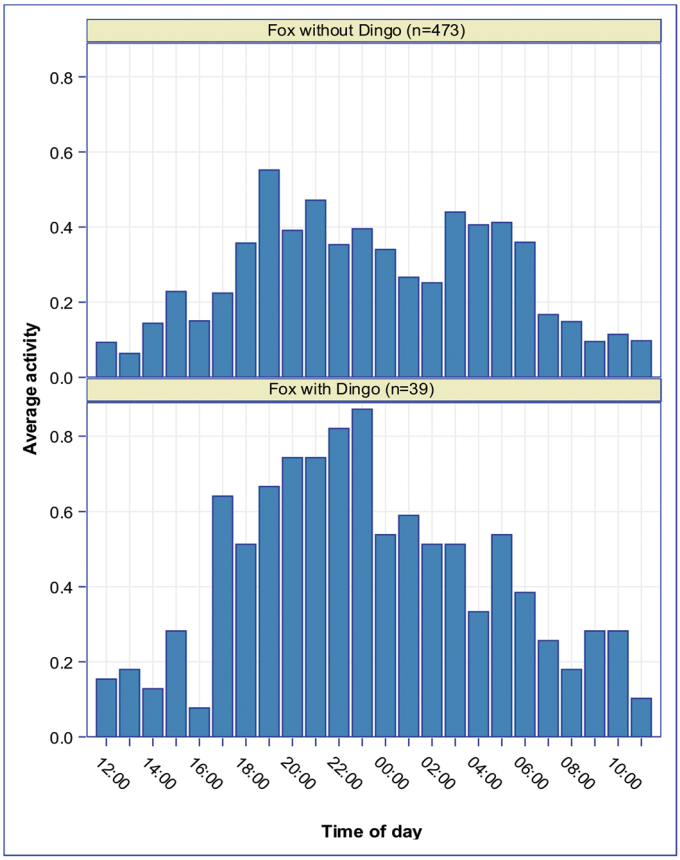

Figure 13. a) the time of day of the movement of foxes in the absence of dingoes/wild dogs; b) the movement of foxes in the presence of dingoes/wild dogs. The correlation between the upper and lower patterns is 0.75. The behaviour of the foxes with respect to time of day only mildly changed with the presence of dingoes/wild dogs. (Note, the graphs run from noon to noon, with midnight in the centre of the graph.)

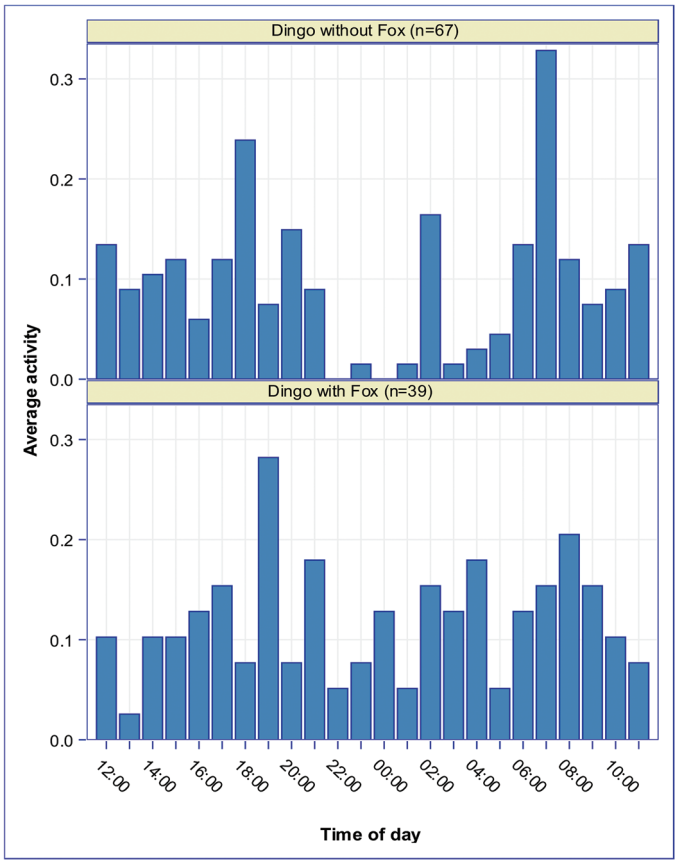

Figure 14 a) the time of day of the movement of dingoes/wild dogs in the absence of foxes; b) the movement of dingoes/wild dogs in the presence of foxes. The correlation between the upper and lower patterns is 0.13. i.e. a negligible correlation revealing a shift in behaviour of dingoes/wild dogs to include considerably more night-time activity when in the presence of foxes.

pictures. Collectively, the different approaches to the data sources lying behind the maps support the case that no one approach to mapping dingoes/wild dogs is adequate for all of NSW in determining its distribution that stretches from the coast to the South Australian border.

We note that the western division is not well served by citizen science survey so far. In fact, Lunney et al. (2017) found that the west is not well served by any survey, with the exception of a few sites where people are undertaking detailed and long-term research. In the case of the sparsely populated western division of NSW, the professional expert opinion on wild dogs as shown in the 2016 DPI map makes a useful contribution on an otherwise almost blank sheet. However, we are aware of the cynical view that this map, showing high densities of wild dogs in north western NSW, could be used to justify the dog fence. If that were the case, such maps would not contribute to science. The resolution is straightforward, add an independent survey, although we can see that with such a low human population density, the options are limited, and alternate techniques would help. We also argue that we are all better off with peer-reviewed publication of information, including distribution maps, which underpin so many conservation and management decisions. The 2016 wild dog map was not part of a publication where the methods are presented for others to see, the only part visible is the map, which is not enough to unequivocally reject the cynic's viewpoints.

In two neat studies of the role of the dingo in ecosystem function, spotlight surveys from 2011-2017 by Feit *et al.* (2019) revealed dingoes to be virtually absent from their study areas inside the dingo fence in the north-west corner of NSW. Similarly, between 2012 and 2016, Rees *et al.* (2019) monitored the numbers of dingoes, red foxes, feral cats, barn owls and small mammals across the dingo fence in the Strzelecki Desert at seven sites - three were on the side of the dingo fence where dingoes were functionally extinct and four were on the side of the fence where dingoes were common. They did note dingo tracks on the inside of the fence, but a dingo was only detected on a single spotlight survey, hence the references to dingoes being functionally extinct. This is consistent

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Table 5. Inter animal times restricted to Dog and Fox (No reset) using All sequences

Times from Fox until Dingo/wild dog all sites all years

Delay duration		Number of captures	
minimum	maximum	Sightings	Accumulated
5 hours	1 day	9	9
1 day	2 days	8	17
2 days	1 week	7	24
1 week	1 month	6	30

Table 6. Inter animal times restricted to Dog and Fox (No reset) using All sequences

Times from Dingo/wild dog until Fox all sites all years

Delay duration		Number of captures	
minimum	maximum	Sightings	Accumulated
1 hour	5 hours	5	5
5 hours	1 day	6	11
1 day	2 days	6	17
2 days	1 week	13	30
1 week	1 month	3	33

Table 7. Inter animal times restricted to Dog and Cat (No reset) using All sequences

Times from Dingo/wild dog until Cat all sites all years

Delay duration		Number of captures	
minimum	maximum	Sightings	Accumulated
1 hour	5 hours	2	2
5 hours	1 day	1	3
1 day	2 days	2	5
2 days	1 week	2	7
1 week	1 month	3	10

Table 8. Inter animal times restricted to Dog and Cat (No reset) using All sequences

Times from Cat until Dingo/wild dog all sites all year

Delay duration		Number of captures	
minimum	maximum	Sightings	Accumulated
5 hours	1 day	3	3
1 day	2 days	1	4
2 days	1 week	1	5
1 week	1 month	1	6
1 month	years	1	7

with the 2016 DPI wild dog map, which shows a low density in the very far north-west corner of NSW. It is such detailed studies as those of Feit *et al*. and Rees *et al*. that bring a much-needed extra dimension to the debate of the dilemma to cull or conserve by giving a detailed statement of dingo occurrence and location and dates. We also note here that scale matters, the spotlight surveys were highly localised compared to the citizen science studies and the methods underpinning the DPI wild dog map. We cannot extrapolate from the spotlight surveys eastward, where the 2016 DPI map shows high density of wild dogs, but we do point to the value of independent survey methods and the value of the publication of information.

FoxScan

FoxScan (2020) is unexpectedly different to the occupancy map for foxes presented in our study. Whereas the map we display has a high level of occupancy across most of the state, with a high level of certainty, FoxScan has a highly truncated distribution, with a concentration on the central coast and the Sydney region and around the ACT, with far fewer presence records from large parts of NSW where our occupancy map reveals high levels of fox presence. We note that FoxScan is a presence-only map, not a reflection of absences which is part of the occupancy map method. We also note that FoxScan is not a project or service designed to help assess the extent of foxes in NSW. Further, a likely explanation for this trend is that because foxes are present in most rural and regional areas, recording their presence into a database is not a high priority to landholders or the general public. Thus, the FoxScan map does not mean that foxes are not as abundant in regional NSW. In contrast, the use of FoxScan was encouraged throughout the central coast, ACT and Sydney (Peter West DPI pers. comm. October 2020). As with wild dogs, the protected areas essentially did not contain many fox records.

Our study did not have an occupancy map for feral cats, so we have no comparison with FeralCatScan. We do note that, in FeralCatScan, there was only a very modest distribution of feral cats in NSW, which would appear to be an obvious under-representation of their distribution. Of these records, there were few feral cats in protected areas, but they did border the protected areas, which indicates that they can freely move across the tenure boundaries We also note that, for most of NSW, the map in Woinarski *et al.* (2019, p 83) has a distribution of feral cats that covers all of NSW, mostly at low density, but with notable patches of high density. The map of feral cat density in Australia, used by Woinarski *et al.*, is from 1992. It points to the problem of gaining a clear picture of occurrence, especially over an area as large as Australia, even for an invasive carnivore as lethal as a cat for our native fauna, although Legge *et al.* (2017) found that feral cats are present on over 99.8% of Australia. The maps in Legge *et al.* (2017) show the sharp changes in model predictions for cat density in natural environments during dry-average rainfall conditions and after extensive rainfall. Feral cat density is fairly uniform across the continent during average-dry conditions, but extensive rainfall events cause an estimated increase in population size in natural environments from 1.4 million after continent-wide droughts to 5.6 million after

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extensive wet periods. The authors also point out that an additional 0.7 million feral cats live in heavily modified environments, such as towns and intensive farms. To that grim set of figures, we can now add that feral cats are widespread in protected areas in eastern NSW.

The dingo and dog maps in the Atlas of Living Australia

The many taxonomic changes for the dingo have caused confusion in the mapping of dingoes. When the *Atlas of Living Australia* is accessed, there is a list of the name changes for the dingo, and the map for the dingo, as *Canis lupus* (Appendix 4a), is similar to the occupancy map we present in Figure 1. However, it does not capture the distribution of dingoes in western NSW. Also, it is largely blank for the rest of Australia. Strangely, when the map for *Canis familiaris* is examined, it fills South Australia and the Northern Territory and parts of Queensland and Western Australia, but very little of NSW (Appendix 4b). So, the distribution of the dingo in Australia appears to be confounded in the *Atlas of Living Australia*, and it thus takes skill in seeing that the source of the problem is the difference in the use of the names, both the scientific and common names. It needs the extra knowledge of the debate over the names to realise that combining the maps is needed to capture the real extent of the distribution of the dingo in Australia from the maps in the *Atlas of Living Australia*. Given that confusion, we advocate using the maps presented in our study, and the DPI expert map, as being as near as you can get to a refined picture of the distribution of dingoes/wild dogs in NSW.

National Wild Dog Action Plan 2020-2030

The *National Wild Dog Action Plan 2020-2030* (NWDAP 2020) does not have a map of the distribution of wild dogs, but the lead-in information (CISS 2020) does have a map, shown here in Appendix 5. It is a simple map of two colours, white and red, with a large swathe of central NSW coloured white, corresponding to no wild dogs. Given the sources, DPI, there is no surprise that it is similar to the DPI 2016 map, which has a much more nuanced distribution. What is clear from the red and white map is that most of Australia has wild dogs, which, from the NWDAP, includes dingoes.

Distribution of registered domestic dogs

Whereas dingoes/wild dogs exhibit a discontinuous distribution within NSW, with a concentration along the coast and ranges, and a greater concentration on the north coast, the distribution of registered domestic dogs showed a concentration around Sydney with a declining east-west trend from the coast, and showed only modest correspondence with their wild counterparts. While it is likely that some of the dingo/wild dog sightings reported in the state-wide, citizen science survey were of free-ranging domestic animals, the converse is also likely, because visually there is no way to discriminate between dingo/wild dog and a domestic dog in the field if the dog looks like a classic dingo, or a wild dog. However, the fact that the two maps differ greatly in the distribution of domestic dogs and their wild conspecifics can be interpreted to mean that the respondents to the survey could distinguish between them. It could be explained simply by considering that people know their own dogs and those of their neighbours, and other dogs, such as those dogs without a collar, are dingoes or wild dogs. Nevertheless, there is the real possibility that domestic dogs are an important source of harm to native animals in NSW, and a particular threat to vulnerable and endangered species, a point already well made globally by Doherty *et al.* (2017).

From the figures from the Office of Local Government, the number of dog attacks reported by all councils for the first quarter of 2020 was 1,121 on people, and 997 on animals. However, assessing the relative importance of these impacts at a population level of native animals requires substantial time and resources, so datasets will be rare. In a detailed study of fire and dogs in Port Stephens, in coastal NSW just north of Newcastle, Lunney *et al.* (2004, 2007) found that dog attacks were the cause of 43% of identified koala deaths and the management of dog-related deaths was seen as the key issue for population survival. In this study, the dogs were regarded as feral or roving dogs. This field assessment was consistent with the findings in a community questionnaire by Lunney *et al.* (2001) that dogs were a major threat to koalas in Port Stephens. Given the geography of Port Stephens, being largely separate from a contiguous forest ecosystem, the dogs were most likely domestic dogs, or domestic dogs that had become feral, but unlikely to be recognised as dingoes because of the long history of European settlement in Port Stephens from 1801 (Knott *et al.* 1998). A graphic photo of a dog having bailed up a koala in a suburban backyard in Coffs Harbour on the mid north coast of NSW is presented in Lunney *et al.* (2016), showing a potentially lethal encounter. With 2.5 million registered domestic dogs in NSW as at the beginning of 2020, there would no surprise if they were making inroads, arguably unmeasured, into local populations of native animals. Such a conclusion adds to the complexity of managing domestic dogs, wild dogs, and dingoes, starting with their relative distribution across the state, identifying individuals in the field, with the issues crossing into the debate of the kill or conserve dilemma. A case could be made that the focus on dingoes and wild dogs, and even foxes, could overlook the impact of domestic dogs on native wildlife. The distribution maps of dingoes/wild dogs and foxes as well as domestic dogs allow these comments to have some standing, and thus further make the case for including studies on distribution as a basic element in population ecology and management.

Pests - do opinions vary geographically?

The questionnaire aspect of the 2006 citizen science survey allowed new information to be added to the mapped distribution. With the presence of the sheep industry on a rural landscape, an industry vulnerable to

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wild dog depredation, one might expect the awareness of dingoes/wild dogs to be high, which may in turn lead to an artificially high reporting rate of wild dogs in sheep areas. Instead, we found that the reporting rate of dingoes/wild dogs as a pest decreased with increasing stocking densities of sheep (and a coincident reduction in the reporting rate of dingoes/wild dog presence). This low reporting rate for wild dogs is consistent with the distribution obtained from the 2016 DPI expert opinion maps and the modelled occupancy generated from our 2006 state-wide citizen survey. In regions of high stocking density of sheep, a small proportion of respondents reported dingoes/wild dogs as being present in areas that the expert opinion, and modelled occupancy maps, showed as being absent, or at very low detectability. There is some evidence of an increase in reporting rate of dogs in sheep areas, however the impacts on the overall results were minimal. There is a number of explanations to these results, first that dingo/wild dog control has been ongoing for over a century (see maps in Glen and Short 2000) and it has been successful in reducing dingo/wild dog numbers to a point in which negative dog versus human interactions are now extremely rare. A second explanation is that a relatively small proportion of the population (e.g. sheep farmers) is directly impacted by dingoes/wild dogs, and the remainder of the population is not impacted by this species, and therefore do not have an opinion and did not answer the question. A third explanation is that graziers who have in past periods experienced conflict with dog attacks on sheep have exited the industry and chosen to raise cattle, or harvest wheat or other crops. That means fewer dog/sheep interactions in areas with dogs, because the sheep have been displaced by cattle or cropping.

The density of sheep did not appear to influence the pest status of dingoes/wild dogs for those that completed the question. The percent of respondents reporting dingoes/wild dogs as a pest was remarkably constant across all sheep density classes. However, the response rate to the question are dingoes/wild dogs pests was lower in areas of lower occupancy of dingoes/wild dogs (e.g. 11% response rate in the Central West) so the absolute number of people that thought they were a pest is also lower. The areas with the highest pest reporting rates (and completion rates of 40%) were coastal areas in northern NSW, where sheep production is uncommon, and dog numbers are high. The high reporting rate could be attributable to the fear of attack, or concerns around the impacts of dogs on wildlife (e.g. koalas) rather than economic concerns. The reporting rate of dingoes/wild dogs, however, was inversely related to the sheep stocking density - in high sheep density areas, fewer people observed dingo/wild dogs, which is likely to reflect the investment in dog control in these areas. In contrast, the presence of foxes was a constant irrespective of sheep density.

The reporting rate of dingoes/wild dogs as a pest, and positive records of dingoes/wild dogs, followed similar, geographic patterns indicating that the community perception of pest status of dingoes/wild dogs appears to be in direct proportion to how frequently they encounter them.

Increasing, decreasing, staying the same?

A fundamental question in ecology and wildlife management is whether a population is increasing, decreasing, or staying the same. Predavec *et al.* (2016) found that population trends identified through community wisdom were similar to the trends identified by traditional research. They found that the community wisdom surveys allowed the question of population change to be addressed at much broader geographical scales and time frames. Studies that apply community wisdom have the benefit, they assert, of engaging a broad section of the community in conservation research and education and therefore in the political process of conserving and managing species. Given these findings, our results for the 2006 citizen science survey need to be part of the overall picture of a species distribution in that it adds the element of change. We found that the dominant opinion was 'staying the same' in seven regions for dingo/wild dog, but with perceptions of increases in four regions (Murray, Riverina, North West and Northern Tablelands). Foxes were recorded as increasing through all the LLS regions in the central part of the state (Murray, Riverina, Central West and North West, Central Tablelands and Northern Tablelands).

The dynamics of change in species distribution: foxes and dingoes in NSW

In a study of the causes of extinction of 24 mammal species in western NSW in the 19th century, Lunney (2001) reported that the fox invaded NSW from the south in the late 1890s and occupied the entire state, apart from the far northeast, by 1915. The study also drew on the research by Short (1998) on rat-kangaroo decline and identified that it was closely associated with the northern advance of the fox. Lunney added that the fox can be considered as the agent that delivered the *coup de grace* to species that were already on the brink of an extinction brought about by some 13 million sheep crowding into a few sparse refuges during intense droughts in an eroding landscape. Similarly, the ecological history by Lunney and Leary (1988) on the impact on native mammals of land-use changes and exotic species in the Bega district, south-east NSW, since settlement recorded that the first foxes near Bega were reported in 1906, near Cobargo around 1908, and by 1909 foxes were increasing throughout the Bega Valley. Thus, within a century, foxes have occupied all of NSW at a high level of occurrence, including within protected areas. This is a graphic picture of change and the unwanted success of an alien invasive carnivore that is a major threat to the native fauna of NSW.

The ecological history of dingoes/wild dogs is one of contraction of range, with large areas in what can be considered as the central division of NSW now largely empty of dingoes, and reduced occupancy in other areas.

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Dingoes/wild dogs are relatively scarce in protected areas, and the high levels of occupancy are now coastal, with greater certainty of occurrence on the north coast. The maps of scalp returns shown in Glen and Short (2000) bear witness not only to a high presence in the central west and nearby regions at the end of the 19th century, but a determination to rid the land of these sheep predators.

Roadkill

We have reported roadkill of dingo/wild dog and fox because we recognise the perpetual threat of roadkill for native fauna, and the danger to drivers of hitting an animal on the road, irrespective of whether or not it is a native species. The high percent roadkill of foxes on highways points to the instant death of an animal from a fast-moving vehicle, whereas on a local road, speeds are likely to be lower, causing less injury if hit, or a better chance of seeing an animal and thus avoiding it. Highways are often four lanes, giving an animal less chance of crossing unhurt. Foxes, for all their adaptations to agricultural landscapes, remain prone to being killed on roads. In turn, the carcasses are scavenged by native birds, which then become victims of speeding vehicles. As Lunney (2013) argues, wildlife roadkill remains as a blind spot in public perception. Dingoes/wild dogs are uncommon roadkill, either they are more easily seen, or quicker, or more likely, simply far less numerous than foxes, with the roadkill reflecting the relative density of the two species in NSW.

WildCount, what are its special insights

The camera results from WildCount identify differences in the distribution of the two canid species within national parks and nature reserves. Dingoes/wild dogs are uncommon, not recorded at most sites, even over the six-year period of the study (2012-2017). The greatest concentration was in the north-east of the state, as well as a marked presence in the south-east, extending to the western slopes of the ranges. In contrast, foxes are common and widespread, being found at most sites.

We note that Catling and Burt (1995) also found that foxes are not common in the north-east of the state, in contrast to wild dogs. What is more striking is the re-analysis by Johnson and VanDerWal (2009) of the data of Catling and Burt (1995), as well as that of Newsome (2001). Johnson and VanDerWal concluded that there was in fact a strong negative relationship between the abundance of wild dogs and foxes in forested environments of eastern Australia. They pointed out that when wild dogs are abundant, foxes are consistently rare or absent, but that when wild dogs are rare, foxes may be abundant, but this is not always the case because factors other than wild dogs also affect the abundance of foxes and may sometimes act to hold fox abundance low even when wild dogs are rare. Thus, the negative relationships of dingo and fox abundance are common in Australia, and may be found in high-rainfall forested environments as well as in semi-arid and arid regions.

A persistent problem is that many studies use the relative distribution of the species to infer a relationship among them, as we have done from the WildCount dataset. The arguments may be logical, but they cannot be regarded as conclusive because drawing plausible opposing conclusions is also possible. Given the state-wide scale at which most of the work is being done, the problem is understandable. Consider one argument that has a thoughtful track record (Letnic *et al.* 2011; Newsome *et al.* 2017) in relation to our view of the WildCount data. That argument notes that that the pairwise interactions and times of activity in our WildCount study show little evidence of dingo-fox interactions at the local camera site scale, but there is a tendency for lower fox occupancy at the larger scale in north-east NSW where dingoes/wild dogs are most concentrated. Such scale effects are to be expected on the premise that if a dominant predator suppresses a smaller one, it is likely to do so only where it occurs at high density over large areas. This may be the case in north-east NSW. That argument could be also be extended to include degraded landscapes outside north-east NSW where wild dog control is less intensive. From our research, we do have another dataset to bring into play on this point, and that is the occupancy maps of dogs and foxes.

The pattern displayed by the occupancy maps differs from the WildCount dataset in north-east NSW with its inverse relationship of dingoes/wild dogs in protected areas. In the occupancy maps both dingoes/wild dogs and foxes are shown at equally high levels. Possible explanations are that the higher dingo/wild dog density in protected areas is sufficient to suppress fox density, but this dominance fades on private land. This may be due to a variety of factors, of which the differing methods may be a contributing factor. Private land is where citizen science, leading to occupancy mapping, has its strength, whereas the method in the protected areas uses cameras. Stepping aside from the methods, one can postulate that the variability in habitat structure is likely to be part of the explanation. This remains a field for research, but one point that can be made is that the two different techniques – cameras and citizen science –add greater explanatory power for a regional assessment where protected areas are a major feature of the region, such as north-east NSW, which also contains rich agricultural landscapes.

Cats were also found to be common and widespread, with most sites having recorded a cat over the study period. A reasonable conclusion to draw is that foxes and cats can be found almost anywhere in the protected areas in NSW, and as recognised threats to our native fauna, there is little comfort in the WildCount maps that our protected areas are safe havens anywhere from these alien invasive predators.

We did not set out to test the proposition that dingoes/wild dogs, foxes and cats exclude one another from occupying an area; in the case of WildCount, the area is being assessed by cameras. Nevertheless, the detailed

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camera records enabled us to test for spatial or temporal shifts that show significant avoidance or co-occurrence. We did this by a step by step procedure. The first was to examine the pairwise interactions of a set of species using WildCount sites. Our findings were that there was only limited evidence for significant interactions, with fox-rabbit significant for 4 of the 6 years of study, and fox-swamp wallaby significant in 4 of the 6 years of our dataset. We found no significant findings for fox-dog, fox-cat, dog-cat, dog-rabbit, dog-swamp wallaby, nor for cat-rabbit, cat-swamp wallaby pairwise interactions. In short, it appears that foxes and their prey, rabbit and swamp wallaby, co-occur, but no large imbalance between co-occurrence (predator to prey) or avoidance (prey from predator). The next step was to examine habitat use, and foxes and dingoes/wild dogs significantly separate within two sub-formations of dry sclerophyll forest. The next step was more detailed, using the time of day recorded by the cameras.

We found that there was a minor effect of the presence of dingoes/wild dogs on the time-of-day behaviour of foxes. The correlation of time of day patterns for foxes without and with the presence of dogs was reasonably high at 0.75 meaning the foxes maintained the times of movement they exhibited when dingoes/wild dogs were not present. In contrast there was an impact of foxes on the time of movement of dingoes/wild dogs. The time of day pattern of dogs without foxes had little prediction ability for the time of day pattern in the presence of foxes with a low correlation of only 0.13. The final step was again to use the details from the camera data, and we found that for the inter-animal times at sites where both dingoes/wild dogs and foxes were recorded, there was little difference between the time since the other species was present. Despite the low numbers for this analysis, there was no basis for considering that either the dingo/wild dog or the fox inhibits the other from being at a site. We have thus found that there are differences in habitat use and behaviour of these two canid species, yet the data do not allow us to point to a spatial or temporal separation that identifies a high level of interactions or avoidance. Our results do, however, identify that these interactions are occurring within the protected areas of the coast and ranges of NSW, thus the dingo/fox story has its own dimensions within national parks and nature reserves, and that warrants its own study and interpretation where vegetation structure and the undegraded nature of the environment appear to play a pivotal role.

WildCount: what have we learnt

The question arises as to whether surveys are a worthwhile and effective management tool, especially surveys in limited locations, such as national parks and nature reserves. Our answer is that without high resolution maps, and trends from repeated surveys, we would be flying blind as to the distribution of the animals that we need to protect, or in the present case, the animals that we need to manage as known threats to the survival to our native fauna. Both our citizen science survey and FeralScan have a distinct limitation as revealed by our comparison with the WildCount surveys within parks and reserves, namely that they are not capable of a substantial and useful set of records for management purposes or policy settings within protected areas. The citizen science and camera surveys are, however, complementary, not alternative techniques if we are to cover the entire landscape. We can conclude that we are better prepared by utilising a range of survey and monitoring techniques that are complementary. To return to our question as to whether such programs as WildCount are worthwhile, we can unequivocally answer yes, they reach where citizen science cannot reach, and expert opinion can be scarce in large tracts of little-known protected areas. We add that the longer WildCount runs, the more valuable it will be at identifying trends, and assessing such impacts as from the bushfires of the black summer of 2019-2020.

Top–down control of mesopredators and herbivores – comments on this debate from our results

We note that Woinarski *et al.* (2019, p50) remark on the ferocity of the debate on the effects of dingoes on cats, foxes and native species and the functioning of Australian ecosystems. They make the observation that if the dingo has a role to play in diminishing the impacts of these mesopredators, then researchers and managers will need to work more closely to realise any potential benefits of the dingo as biodiversity regulator. With that cautionary note in mind, we consider a few of the positions in this debate and compare the salient features with our findings.

Bob Harden, a long-time colleague of one of us (DL) in NSW National Parks and Wildlife Service, had many stories to tell of the difficulty of studying dingoes in the forested national parks near Armidale, on the northern tablelands. Harden (2001) commented that the relationship between the abundance of dingoes and their major prey species suggests that dingoes have a functional role in ecosystems. Harden was firm in his opinion that there is little evidence to support the widely-held belief that dingoes or other wild dogs limit the distribution or abundance of foxes in NSW. He acknowledged that while an inverse relationship between wild dog and fox abundance has been observed, it remains to be demonstrated that wild dogs cause a reduction in fox abundance. Harden (1997) had previously reported that foxes were present in at least 89% of the 133 NPWS parks and reserves with wild dogs. Thus, he concluded, there is little evidence that wild dogs actually exclude foxes.

Brook *et al.* (2012) noted that while apex predators can benefit ecosystems through top-down control of mesopredators and herbivores, they are often subject to lethal control to minimize attacks on livestock. Using camera surveys in the Australian rangelands properties, their results identified that effective dingo control not only

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leads to higher abundance of feral cats, but also allows them to optimize hunting behaviour when dingoes are less active. They concluded that in areas managed for conservation, stable dingo populations may thus contribute to management objectives by restricting feral cat access to prey populations. Greenville *et al.* (2014) tested the interactions among sympatric predators with fluctuations in the background availability of resources using camera data to uncover spatial and temporal interactions between a top predator, the dingo, and the mesopredators - fox and feral cat - during population booms, declines and busts in numbers of their prey in a model desert system. They found that dingoes predictably suppress abundances of the mesopredators and that the effects are strongest during declines and busts in prey numbers. They concluded that the dingo provides net benefits to prey populations by suppressing mesopredators during prolonged bust periods when prey populations are low and potentially vulnerable.

The dingo/cat WildCount survey data were confined to the protected forested eastern NSW, not the rangelands nor desert ecosystems. This difference may be sufficient to account for the contrast with our results that do not allow similar conclusions to be drawn, either from our pairwise interactions at cameras or our finding that dingoes/wild dogs have a limited distribution in the national parks and nature reserves compared with foxes and cats. The difference could lie in the considerable differences in the landscapes, with the point being that the differences in the vegetation structure and the comparatively intact landscape alter the dynamics of the relationships. However, we note that Fancourt *et al.* (2019), working in the semi-arid, sub-tropics near the eponymous town of Dingo, concluded that dingoes had no negative effect on the probability of cat presence, with the probability of detecting a cat on the national park being significantly higher in areas with dingoes than in dingo-free areas. This finding adds yet one more level of complexity that needs to be taken into account as we refine our view that the variations in the landscape, including protected areas, contribute to the patterns of co-existence, or no co-existence, of these predators. As Glen *et al.* (2014) point out, under the heading of 'Managing cats, foxes and wild dogs', the net impact of predators can be positive, negative or neutral, depending of the context of the ecosystems, with the role of the predators varying depending on the other species present, as well as habitat, and ecosystem productivity. There is clearly more research to be done.

A technical matter that needs to be considered is that the effectiveness of cameras and their placement, e.g. on tracks, off tracks, in forests differs from their ability to detect interactions compared with more open habitats. However, the data we did collect did not allow us to point to interactions of one species driving the populations of other species. The problem becomes more complex when the results of a study by Colman *et al*. (2014) are considered.

In their detailed study, also in forested conservation reserves in eastern NSW, which featured counts of tracks on sand pads on forest roads, Colman *et al.* (2014) found differences in the relative numbers of mammals and the complexity of understorey vegetation between areas where dingoes had been removed by 1080 baits compared to those without removal. These results, the authors point out, were consistent with studies in deserts and forests where there were negative relationships between the presence of dingoes and the abundance of macropods and foxes, and positive relationships between the numbers of dingoes and small mammals. They concluded that the broad-scale benefits that dingoes appear to provide for ground-dwelling small and medium-sized mammals provide evidence that dingo control programs in conservation reserves may be counter-productive from a biodiversity conservation perspective. The authors add that: "such strategies are likely to be controversial owing to the adverse impacts that dingoes can have on livestock producers." We can observe that controversy continues to dog such management conclusions, with Allen (2015) being quick to put forward an alternative hypothesis.

The finding by Leo *et al.* (2019), in their study in a tropical savannah linking apex predator suppression to restructuring of ecosystems, was that dingo control is linked to increases in the abundance of macropods and feral cats and decreases in the density of understorey vegetation and numbers of rodents. These findings, the authors point out, were consistent with previous studies of dingo control in desert and forest ecosystems. The authors further point out, their results, and earlier studies investigating the effects of dingo removal in deserts and forests, suggest that dingoes' suppressive effects on herbivore and mesopredators occur at the same time.

Also working in the top end, Stobo-Wilson *et al.* (2020a) concluded that the protection and enhancement of habitat structural complexity could reduce the exposure of small- and medium-sized mammals to feral cats and dingoes. This can most likely be achieved through improved fire and feral herbivore management, which, they point out, is a more feasible management option than lethal predator control. Stobo-Wilson *et al.* (2020b), explaining their findings in a more relaxed style in *The Conversation,* found no evidence that dingoes influenced the distribution of feral cats, but rather, they found that survey sites with more dingoes had fewer native small mammals, suggesting a negative impact by dingoes. They add that, unlike cats, culling dingoes is not an option because they provide other important ecological roles and are culturally significant for Indigenous (and non-Indigenous) Australians.

The role of complex vegetation structure in an undegraded landscape

One inference we draw from the range of research findings is that the complex native vegetation in the forested

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protected areas in eastern NSW is sufficiently different to the more open landscapes, such as the arid and semi-arid lands, particularly given that grazing by sheep and cattle has been extensive in these inland ecosystems, to thereby play a role in enabling cats, dingoes/wild dogs and foxes to co-exist, as we found, in a way not possible in more open and/or degraded habitats. This view adds to the value of dedicating and managing undegraded natural areas as national parks and nature reserves for conserving our native fauna. It also adds to the value of such monitoring programs as WildCount to help us understand how species survive in close proximity within our protected areas. The idea that protected areas are valuable for conserving fauna has been contested (Lunney 2017), so the results of our study, and those of other researchers, add weight to their value by providing further proof of the benefits of native vegetation that has not been degraded.

Of course, as researchers, we encourage more research on dingo/wild dog ecology if we are ever to understand and manage both our native fauna and our natural areas. Protected areas, such as Nadgee Nature Reserve, a coastal forest in the south-eastern corner of NSW, has been an ideal, long-term study site for dingo ecology for the CSIRO team led by Alan Newsome (Lunney *et al.* 2013). In contrast to Nadgee, much of the adjacent Eden region has been the subject of wood chipping – a high intensity logging regime. In one study of the diet of dogs and foxes in the coastal forests in the north-eastern part of the Eden region there was no difference between dogs and foxes in the two years following logging and a severe fire through the forest. Fifteen years later, the diet of the two species had separated along the lines found by others when comparing the diets of these two canids (Lunney *et al.* 1990, 2002). Although Lunney *et al.* (1990, 2002) use the term "dog", they were locally considered to be wild dogs and these coastal forests were regularly laced with 1080 baits to reduce dog numbers. We note here that these wild dogs were in the same local coastal stretch as Nadgee Nature Reserve, where the dogs were called dingoes.

In their review of dingo diets, Doherty *et al.* (2019) concluded that dingoes have a flexible and generalist diet that changes in relation to both spatial and temporal variation in prey availability. They also found that the presence of threatened species in dingo diets is consistent with direct observations of dingo predation on remnant mammal populations. These species, they reasoned, presumably co-existed with dingoes prior to European colonisation, but today, "a combination of small population sizes, predator naivety of reintroduced animals and interactions between multiple threatening processes (e.g. altered fire regimes, habitat loss, and high rates of predation by red foxes and/or feral cats) means that some species are particularly vulnerable to even low levels of predation". This conclusion can be applied to our understanding of the diets of the dogs in the logged, burnt coastal forests of the Eden region of south-east NSW (Lunney *et al.* 1990, 2002). A conclusion that we draw is that the degraded forest, post-logging and post-fire, was opened up for easy predation by both canid species, but as the forest regrew, the vegetation became more dense, providing more cover for prey and forcing the predators to be more circumscribed in their hunting strategies. The point of these observations is that any account of the interactions of dingoes/wild dogs, foxes and cats depends not only on tenure, but on the level of degradation of the landscape, including forested landscapes, and the temporary opening up of the forest in a post-fire world. It seems reasonable to predict that any studies of the interactions among these predators will change following the black summer of the 2019-2020 bushfires in the forests of eastern Australia.

Our results are in general agreement with the review by Dickman *et al.* (2021) of the interactions among these large predators and their prey in that the 40 odd studies they considered indicate a complex interplay between environmental conditions and dingo predator/prey dynamics. To that suite of factors, we add several additional behavioural findings from camera data, and higher resolution distribution maps. We also add the importance of tenure, specifically whether the land is private, or a national park or nature reserve. However, within the limits of our datasets, we did not find the exclusion of one species by another had occurred, specifically dingo/wild dogs excluding foxes, but we did find a significant impact by foxes on the time of day of the activity of dingo/wild dogs within forested protected areas of eastern NSW.

Conclusions

By combining two primary survey methods - citizen science and cameras - we have determined, at a high level of detail, the distribution of dingoes/wild dogs in New South Wales, both within and beyond the forested national parks and nature reserves of eastern NSW. When the expert opinion map from DPI, especially for the western division, is added to the account, we now have a more complete picture of the distribution of dingoes/wild dogs in NSW. We consider that these maps make a valuable contribution to our understanding of the ecology of these vexatious animals, both for conservation and wildlife management. We note that the distribution of dingoes/wild dogs does not cover the state by any means, but the scalp returns from the late 19th century produced a different portrait of the distribution of dingoes in that they had been much more widely distributed. Thus, our maps are snapshots of the early 21st century distribution of dingoes/wild dogs.

A stand-out feature from all the datasets we have presented is the marked differences in the distribution of the two canid species, with the fox being much more widespread and pervasive in the landscape, both on private land and national parks, than dingoes/wild dogs. The camera results identify differences in the distribution of the two species within national parks in eastern NSW, and the time of movement data reveal that foxes disrupt the movement patterns of dingoes/wild dogs in the WildCount study area,

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but not the converse to any great extent. In the course of the last century, dingo/wild dog distribution and density has contracted, whereas the fox has invaded and occupied the entire state at a high density. Even though the maps show a contraction of the range and density of dingoes/wild dogs, the citizen science survey identifies increases in population sizes, as well as increases in foxes. These results can be interpreted as the density rising in some locations, and the almost universal sense of regarding the fox as a pest, with the dingo/wild dog also registering a high level of being regarded as a pest, irrespective of its density in a region. We note, however, that the dingo/wild dog is not completely assigned to pest status by the respondents in the citizen science survey, which may show some level of tolerance for the native dog, or even a deep appreciation, as is evident in the study by Philip (2021).

These results allow new ideas to emerge: citizen science and cameras are complementary, not alternative techniques; foxes are an inescapable threat on all parts of the landscape, whereas dingoes/wild dogs are concentrated, principally in the coastal regions, particularly the north-east of NSW; the new methods and the new analyses, especially occupancy modelling from citizen science survey, have produced higher resolution maps than have been previously available; and the interactions between dingoes/wild dogs and foxes are more complicated than can be provided by any one explanation – from our results, an intact landscape plays a role, landscape here meaning both vegetation type and the tenure and management of national parks and nature reserves compared with private land, which is by and large, agricultural land.

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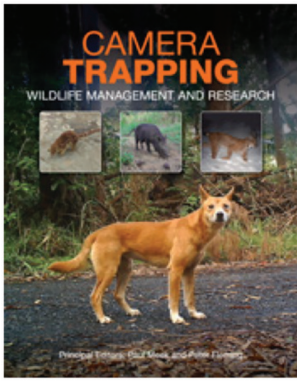
APPENDIX

Appendix 1. "Dingo" is defined in the Macquarie Dictionary (5th edition) as "1. A wild dog, *Canis lupus dingo*, usually tawny-yellow in colour, with erect ears, a bushy tail…". From that description, the wild dog depicted on the front cover of *Camera Trapping* is a dingo, or could be considered to be dingo in a citizen science survey or a camera trap record. However, given that the dictionary defines dingo as a wild dog, the questions and answers are circular. The Atlas of Living Australia (2020) description is as follows: "Dingos are typically ginger-colored with white points in Australia, but black and tan, or black and white pelage patterns of purebred individuals may be found." This description also fits the animal on the cover of *Camera Trapping*.



Appendix 2. The changes in the distribution of the dingo, as assessed by scalp returns, on page 436 in the paper by Glen and Short (2000) as a point of comparison with the modern distribution as presented in Figures 1, 4a and 10. The caption to the figure in Glen and Short reads: "Figure 3. Distribution and relative density of dingoes as assessed by scalp returns for the period (a) 1886-1890. (b) 1996-1900. (c) 1906-1910. (d) 1916-1920 and (e) 1926-1930."

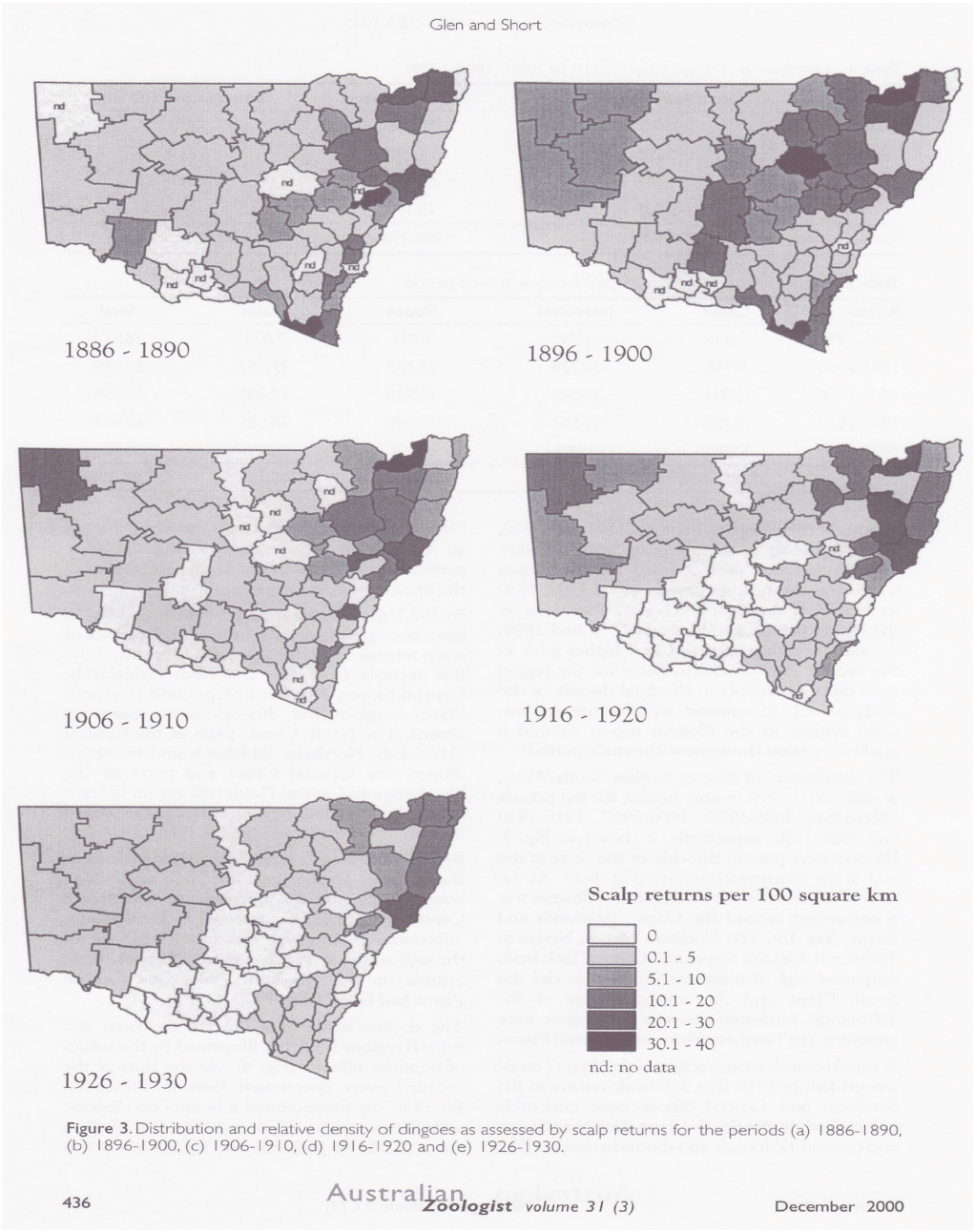


Figure 3. Distribution and relative density of dingoes as assessed by scalp returns for the periods (a) 1886-1890, (b) 1896-1900, (c) 1906-1910, (d) 1916-1920 and (e) 1926-1930.

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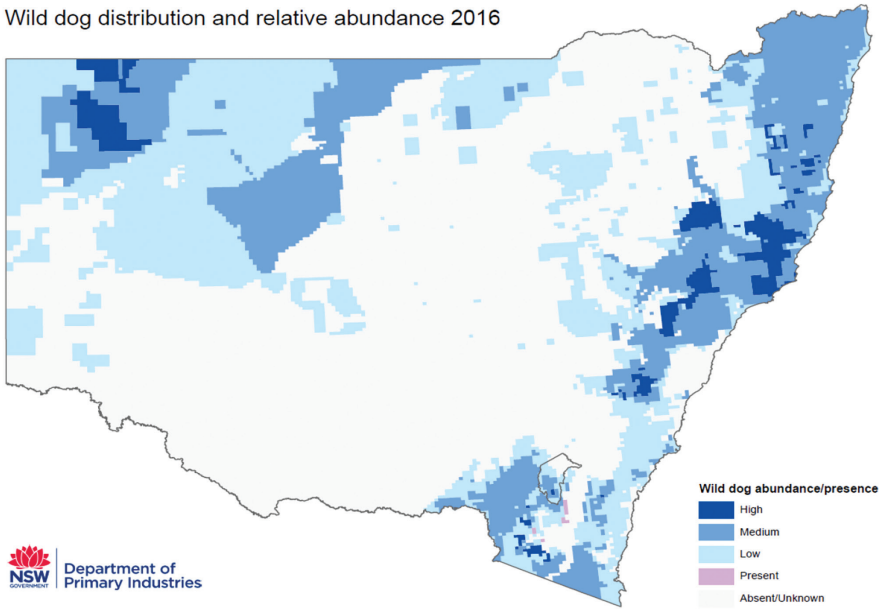
APPENDIX

Appendix 3. Mapped results of the pest animal survey by DPI for NSW. This map describes the distribution and relative abundance of wild dogs throughout NSW and the ACT using information contained within formal datasets and records and perception-based information from land managers based on their experiences and observations. The legend next to the five boxes with colours reads, "wild dog abundance/presence". The five colours are, from dark blue at the top, stating "high", the others in descending order are "medium, low, present and absent/unknown", the last box is white.

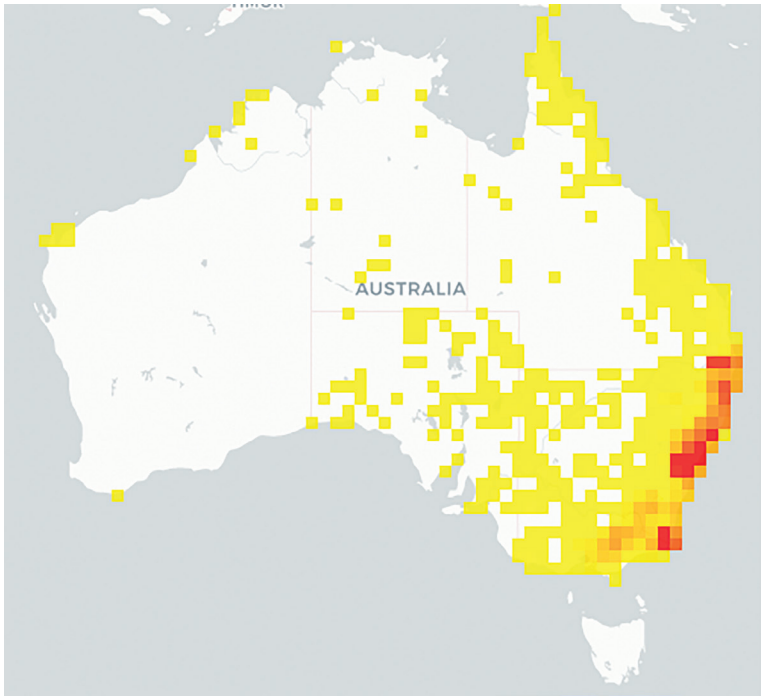


https://www.dpi.nsw.gov.au/biosecurity/vertebrate-pests/pest-animals-in-nsw/wild-dogs/wild-dog-biology (last accessed 27 July 2020)

Appendix 4. Appendix 4a shows the distribution of the dingo as *Canis lupus*, with 4b showing *Canis familiaris* in the Atlas of Living Australia.

https://bie.ala.org.au/species/urn:lsid:biodiversity.org.au:afd.name:3064f20b-f6de-4375-8377-904cbd6cf9fa#overview (last accessed 1 August 2020)

Appendix 4a.



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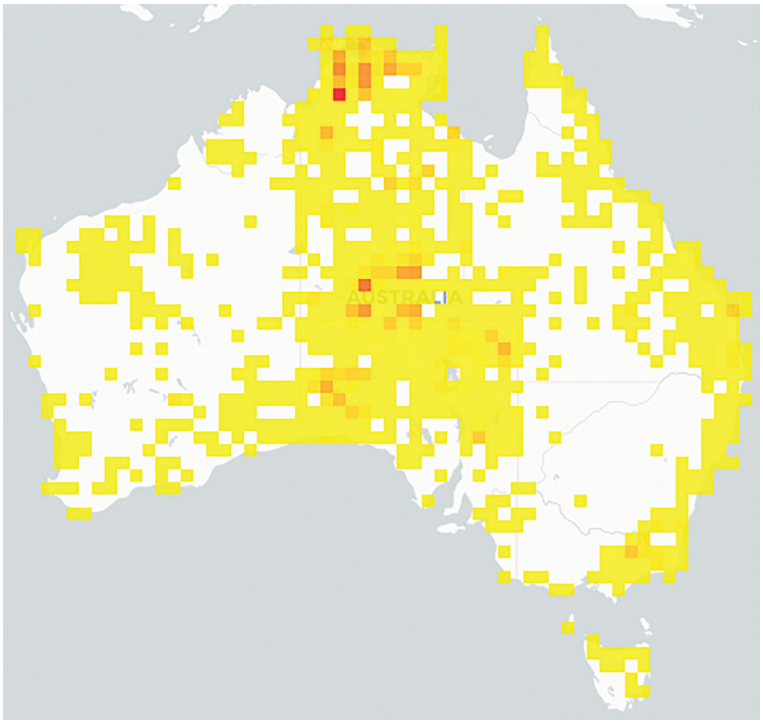
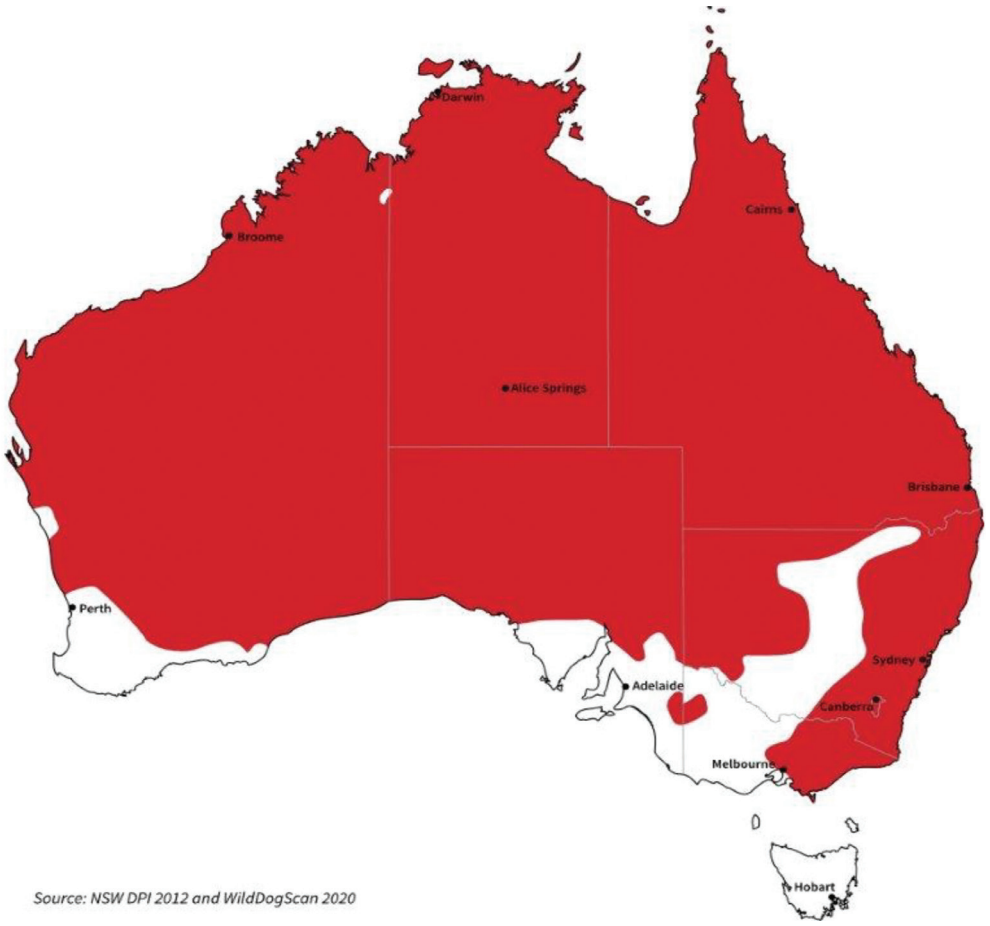
APPENDIX

Appendix 4b.



Appendix 5. Map from the National Wild Dog Action Plan.



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